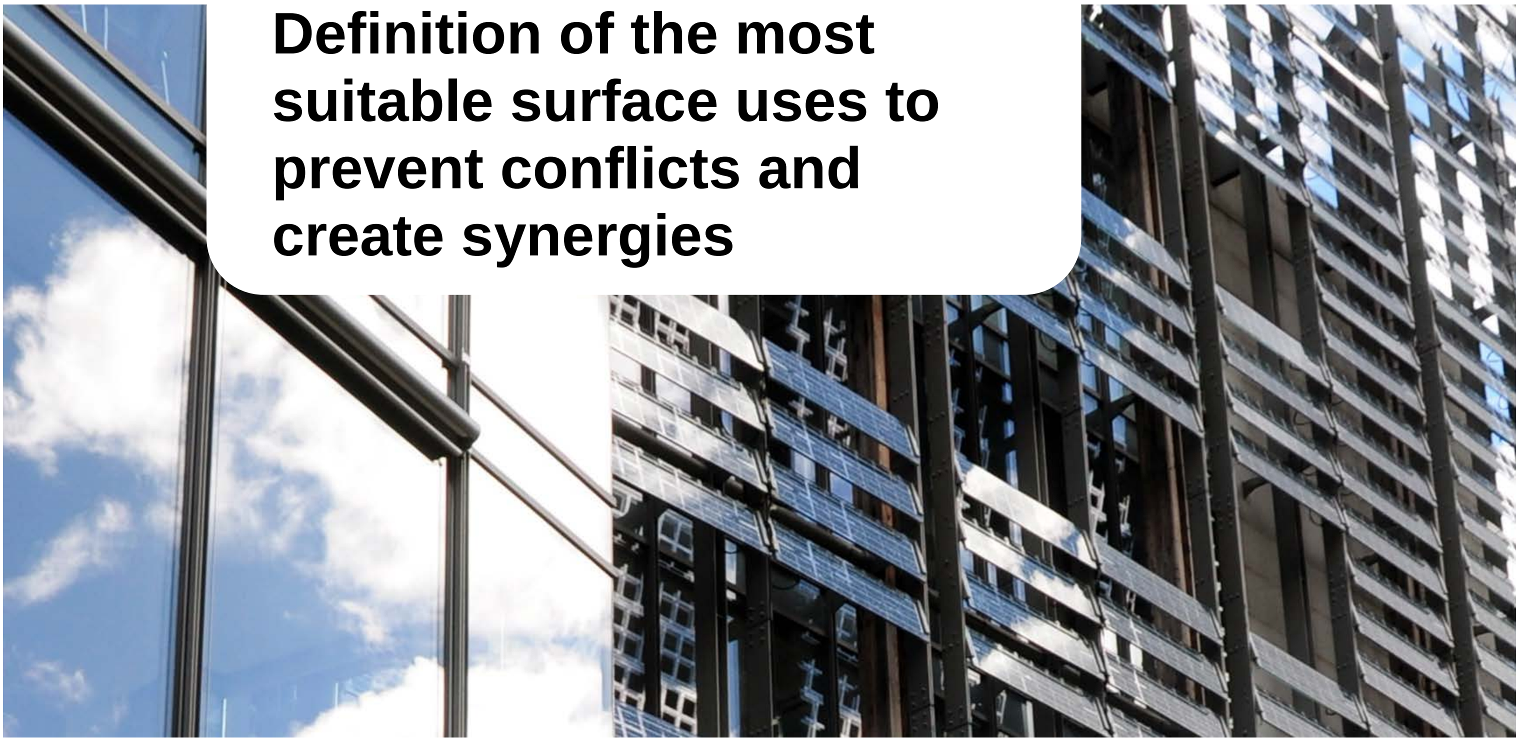
Surface Uses in Solar Neighborhoods



Definition of the most suitable surface uses to prevent conflicts and create synergies

IEA SHC TASK 63 | SOLAR NEIGHBORHOOD PLANNING

Technology Collaboration Programme
by iea

Surface Uses in Solar Neighborhoods

This is a report from SHC Task 63: Solar Neighborhood Planning and work performed in Subtask B: Economic Strategies and Stakeholder Engagement

Editor: Silvia Croce

Authors: Silvia Croce, Caroline Hachem-Vermette, Matteo Formolli, Daniele Vettorato, Mark Snow

Reviewer: Maria Wall

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Editor

Silvia Croce
Eurac Research
Institute for Renewable Energy
Urban and Regional Energy Systems Group
Italy

Reviewer

Maria Wall
Lund University
Department of Building & Environmental Technology
Division of Energy & Building Design
Sweden

Authors

Silvia Croce
Eurac Research
Institute for Renewable Energy
Urban and Regional Energy Systems Group
Italy

Caroline Hachem-Vermette
University of Calgary
School of Architecture, Planning and Landscape
Canada

Matteo Formolli
Norwegian University of Science and Technology
Department of Architecture and Technology
Faculty of Architecture and Design
Norway

Daniele Vettorato
Eurac Research
Institute for Renewable Energy
Urban and Regional Energy Systems Group
Italy

Mark Snow
Australian PV Institute
Australia

Contributors

Rossana Paparella
University of Padova
Department of Civil, Environmental and Architectural Engineering
Italy

Solar Heating and Cooling Technology Collaboration Programme (IEA SHC)

The Solar Heating and Cooling Technology Collaboration Programme was founded in 1977 as one of the first multilateral technology initiatives ("Implementing Agreements") of the International Energy Agency.

Our mission is *"Through multi-disciplinary international collaborative research and knowledge exchange, as well as market and policy recommendations, the IEA SHC will work to increase the deployment rate of solar heating and cooling systems by breaking down the technical and non-technical barriers."*

IEA SHC members carry out cooperative research, development, demonstrations, and exchanges of information through Tasks (projects) on solar heating and cooling components and systems and their application to advance the deployment and research and development activities in the field of solar heating and cooling.

Our focus areas, with the associated Tasks in parenthesis, include:

- Solar Space Heating and Water Heating (Tasks 14, 19, 26, 44, 54)
- Solar Cooling (Tasks 25, 38, 48, 53, 65)
- Solar Heat for Industrial and Agricultural Processes (Tasks 29, 33, 49, 62, 64)
- Solar District Heating (Tasks 7, 45, 55, 68)
- Solar Buildings/Architecture/Urban Planning (Tasks 8, 11, 12, 13, 20, 22, 23, 28, 37, 40, 41, 47, 51, 52, 56, 59, 63, 66)
- Solar Thermal & PV (Tasks 16, 35, 60)
- Daylighting/Lighting (Tasks 21, 31, 50, 61)
- Materials/Components for Solar Heating and Cooling (Tasks 2, 3, 6, 10, 18, 27, 39)
- Standards, Certification, and Test Methods (Tasks 14, 24, 34, 43, 57)
- Resource Assessment (Tasks 1, 4, 5, 9, 17, 36, 46)
- Storage of Solar Heat (Tasks 7, 32, 42, 58, 67)

In addition to our Task work, other activities of the IEA SHC include our:

- ➢ SHC Solar Academy
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Contents

1 Synopsis

This report has been completed through international collaboration under the International Energy Agency (IEA) Solar Heating and Cooling (SHC) Programme - Task 63 on Solar Neighborhood Planning. Specifically, the work contributes to Task 63 Subtask B - Economic Strategies and Stakeholder Engagement by identifying and discussing the potential usage of different urban surfaces in harvesting solar energy. Special focus has been placed on the identification of conflicts and synergies among solutions, and their contribution to the major climate resilience and sustainability objectives defined by solar neighborhoods.

The goal is to foster the utilization of urban surfaces in solar neighborhoods by integrating the exploitation of solar energy with the enhancement of climate resilience and sustainability within urban planning and design processes.

This report presents a collection of urban surface uses, discusses their characteristics, addresses the solar suitability and benefits of different urban surfaces, and presents examples from real cases. The potential conflicts and synergies among solar active and passive strategies and other uses are analyzed with the view of a multiple and integrated utilization of urban surfaces.

2 Introduction

During the design process of neighborhoods, it is often assumed that the available areas with suitable solar irradiation levels should be used to install and/or integrate active or passive solar energy systems (e.g. photovoltaic or solar thermal panels, glass surfaces, etc.) to increase renewable energy production and energy efficiency. However, a wide range of solutions aiming at climate change adaptation and mitigation, and sustainability are closely linked to solar radiation, either by exploiting it (e.g. green solutions and urban agriculture for the growth of vegetation), or reacting to it (e.g. cool materials reflecting sunlight to decrease surface temperatures). In this broader context, the design of solar neighborhoods - requiring the definition of locally adapted, resource-efficient, and systemic interventions - should consider all these potential solutions.

The experts of IEA SHC Task 63 developed a collection of solutions suitable for the application in solar neighborhoods, starting from active and passive solar energy systems but broadening to several other sectors. The results are presented in this report, using the urban surfaces as a basic element for describing the spatial structure of neighborhoods and identifying the areas on which the different solutions might be applied (Croce and Vettorato, 2021).

2.1 Urban surfaces and their uses

The term ***urban surfaces*** encompasses all surfaces that characterize physically and morphologically the built environment from a radiative, thermal, and hydrological perspective (Croce, Vettorato and Paparella, 2019). These include the horizontal and vertical surfaces of the ground and the building envelopes, which can be characterized by different materials and can host several functions.

Urban surfaces significantly impact the quality of life in built-up areas, as well as their environmental conditions, as the major urban phenomena (e.g. UHI, floods, loss of urban biodiversity, etc.) are influenced by their characteristics. On the other hand, they have an unprecedented exploitation potential for producing resources, such as energy, food or greening, and reducing climate change-related impacts (Kellett, 2011).

To define the comprehensive way in which urban surfaces can be designed and exploited, the term ***surface use*** has been selected. The term includes all the materials and solutions that can build the urban surfaces or be applied on them in the three-dimensions of the urban environment (Croce and Vettorato, 2021).

2.1.1 Multiple benefits provided by the use of urban surfaces

To better frame the contribution of urban surfaces and their characteristics to resilience and sustainability in solar neighborhoods, and to define their role in tackling the challenges related to climate change and urbanization, some major aims to be pursued in urban areas have been defined and aggregated. In this framework, the benefits provided by each surface use have been identified from the literature to define the level of contribution to the above-mentioned objectives. These have been grouped as follows.

Climate resilience refers to the capability of cities to protect their inhabitants and infrastructure from the effects of climate change, and from extreme weather events. Major benefits include (i) urban climate regulation, (ii) urban water management, (iii) air quality amelioration, and (iv) habitats and biodiversity preservation.

Sustainability refers to the efficient use of resources in urban areas. Benefits encompass (i) energy self-reliance, (ii) food provision, and (iii) freshwater availability.

3 Urban surfaces: definition and classification

In Task 63, urban surfaces are used as a basic element for describing the spatial structure of solar neighborhoods and identifying the areas on which the different solutions might be applied. They are classified in two main categories, i.e. ground and building surfaces, and several sub-categories (Figure 1). The categorization, based on Croce and Vettorato, 2021, and has been jointly discussed and further elaborated with Task 63 experts. It has been based on three criteria: i) main function of the surface, ii) characteristic of its material, and iii) geometrical features.

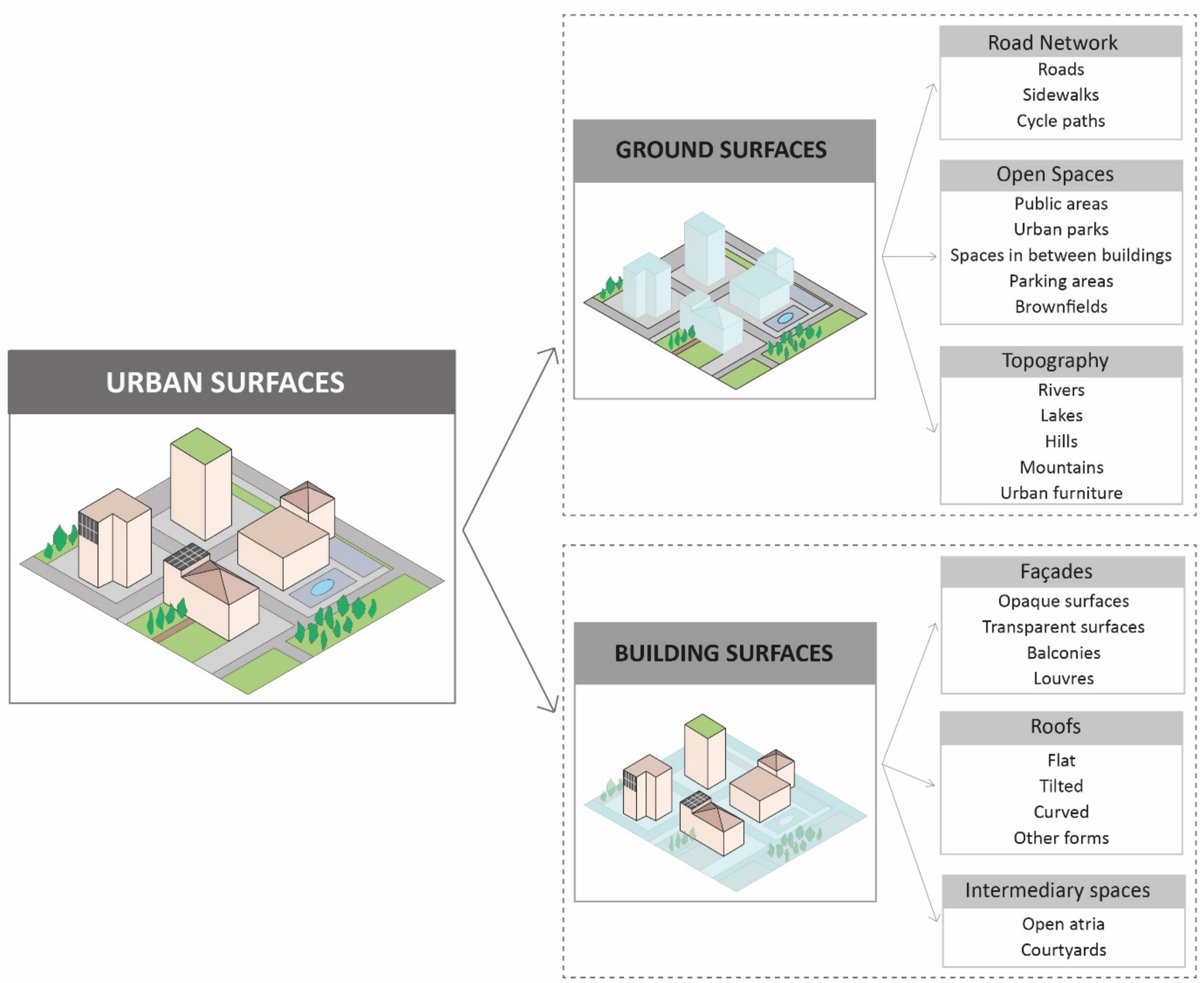


Figure 1. Classification of urban surfaces in Solar Neighborhoods.

3.1 Ground surfaces

Ground surfaces have been divided into road networks, open spaces, and topography.

Road networks include surfaces that are commonly paved, and serve for transit of vehicles and movement of pedestrians: roads, pathways cycle paths.

Open spaces encompass:

- public areas: characterized by predominantly sealed, impermeable surfaces, and primarily designed as publicly accessible areas;
- urban parks: characterized by predominantly unsealed, permeable, vegetated surfaces;
- spaces in between buildings: including residual spaces between building and road networks, and private or semi-private areas such as courtyards, gardens;

- parking areas;
- brownfields: unused areas within the urban boundaries (e.g. abandoned factories, etc.)

Topography includes all the features, natural or man-made, which modify the geometry of the overall surface of an urban area, i.e. rivers, lakes, hills, mountains, and urban furniture.

3.2 Building surfaces

Building surfaces have the common function of enclosing and protecting the interior spaces of buildings. Based on material and geometrical characteristics, they can be classified as follows:

- Façades: opaque surfaces, transparent surfaces, balconies (i.e. main elements that emerge from the façade and modify its geometry), and louvres.
- Roofs: classified by their geometrical form, i.e. flat, tilted, curved, or other forms.
- Intermediary spaces: courtyards and open atria.

4 Surface uses in Solar Neighborhoods

The solutions for surface uses in solar neighborhoods have been collected through a comprehensive literature review, and categorized based on their main characteristics and principal benefits (Figure 2).

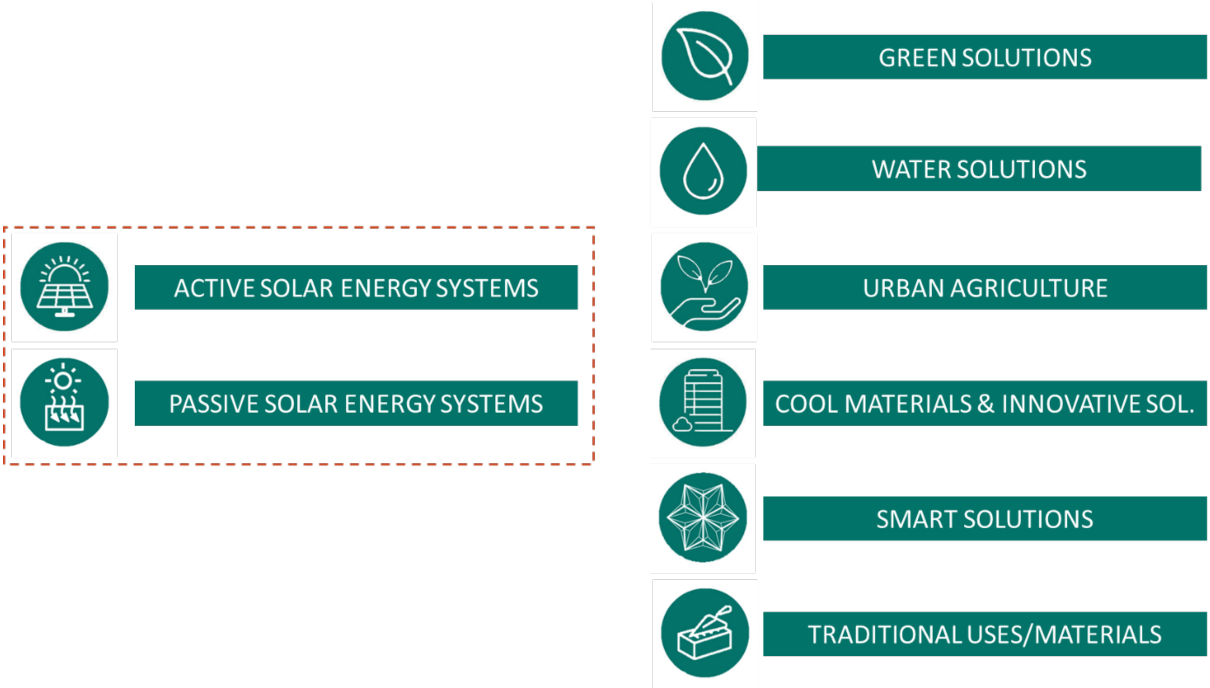


Figure 2. Classification of urban surface uses in Solar Neighborhoods.

Surface uses have been systematized into eight major clusters as follows.

Two clusters directly relate to solar energy:

- *Active solar energy systems*: using renewable energy sources (RES) for the generation of energy or heat in urban areas (Delponte and Schenone, 2020);
- *Passive solar energy systems*: exploiting sun's energy, geographical features and climate, and building materials to heat and cool buildings, and to guarantee suitable daylight levels (Eicker, 2003).

Six clusters are indirectly exploiting solar energy:

- *Green solutions*, which provide environmental benefits, through various types of vegetation in the urban environment (Bowler et al., 2010; Zölch et al., 2016);
- *Water solutions*, which make use of water for multiple purposes, including storm-water management and evaporative cooling (Bao et al., 2019; Ulpiani et al., 2019; Wang et al., 2019);
- *Urban agriculture* for the provision of food products from different types of crops and animals, as well as non-food products, within the city boundaries (FAO, 2019);
- *Cool materials and innovative solutions:* artificial elements, which can maintain lower surface temperatures compared to conventional building and ground materials (Synnefa and Santamouris, 2016; Pisello, 2017);
- *Smart solutions*: innovative technological solutions to respond to the environmental conditions (i.e. responsive / kinetic façades) or to illuminate and animate the urban surfaces;

- *Traditional uses/materials*: materials commonly used on urban surfaces (e.g. asphalt, concrete, glass, etc.) or usual functions.

The following sections present and discuss the major solutions for the use of urban surfaces, both already available on the market and under development, subdivided in previously discussed clusters.

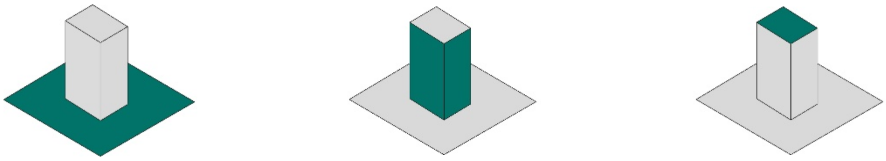
4.1 Surface use sheets

In this report, the information about each solution for surface use has been presented through "Surface use sheets". The template is structured to provide the following information:

SURFACE USE

Description of the surface use, its features and characteristics.

Suitable surfaces — *Identification of the areas on which each surface use might be applied*



Ground surfaces | *Building surfaces - Façades* | *Building surfaces - Roofs*

Benefits — *Identification of the benefits provided by each surface use to define their role in tackling the challenges related to climate change and urbanization. The level of contribution to climate resilience and sustainability objectives is defined as follows:*

- *primary benefits*
- *secondary benefits*

Climate resilience	***Sustainability***
Urban climate regulation	*Energy self-reliance*
Water management	*Fresh-water availability*
Air quality amelioration	*Food provision*
Habitats and biodiversity preservation	

Examples — *Images of the application of the surface uses in different urban contexts worldwide*

References — *References to scientific literature*

4.2 Active solar energy systems

Active solar systems are able to transform the incoming radiation into heat, cooling or energy, i.e. solar thermal (ST) and photovoltaics (PV), using the surfaces of the building envelope or other elements of the urban landscape (Lobaccaro *et al.*, 2019).

4.2.1 Energy systems for the building envelope

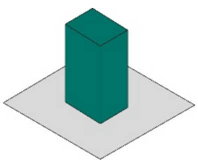
PV / BIPV

Photovoltaics (PV) convert solar radiation into electricity using semi-conducting materials. Two major module technologies are available on the markets: crystalline products (i.e. monocrystalline and polycrystalline), made from crystalline silicon, and thin-film products, which typically incorporate one or more thin layers of photovoltaic material on substrate, usually glass, metal or plastic.

Building-integrated photovoltaics (BIPV) include several solutions for the integration of PV into various parts of the building envelope.

- *Façade systems*: PV technologies can replace the entire external layer or the whole façade system.
    - Opaque façades: can be subdivided into cold and warm. In the first case, PVs are usually added as a cladding element. In the second, PV might be integrated into curtain wall systems, either on the transparent or opaque part.
    - Semi-transparent façades: in the case of crystalline cells used in semi-transparent façade surfaces, the distance among each cell can be defined to control the level of transparency and the final aesthetic effect. Semi-transparent crystalline cells can also be employed. Semi-transparent thin-film modules are also available on the market.
- *Roof systems*: on roofs, PV components can be added on the external surface, substitute the external layer, or the entire technological system.
    - Tilted roofs: several products, both with crystalline and thin-film technologies, were developed for roof tiles, shingles and slates to aesthetically match common roof materials.
    - Flat roofs: the most diffused solutions include added systems with racks supporting standard glass-Tedlar modules, or tilted rack systems with thin-film laminates. Other possibilities encompass the seamless integration on the roof of crystalline modules with plastic substrates, and the use of flexible laminates with thin-film technologies.
    - Semi-transparent roofs: PV systems can also be used as a roof covering, mainly by using semi-transparent crystalline or thin-film technologies in skylights. Such solutions combine energy generation and daylight performance, ensuring a comfortable indoor luminous environment and regulating the transmitted sunlight to reduce building cooling demands.
- *External devices:* PV can also be integrated in external elements of the building, such as shading devices, louvres, balconies or movable shutters.
    - Shading systems have been developed to combine the benefits of shading systems with the production of renewable energy. Such solutions often integrate glass-glass components with semi-transparent crystalline or thin-film modules.
    - Balconies offer the opportunity to integrate both glass semi-transparent modules and opaque systems, also depending on the aesthetic requisites.

Suitable surfaces



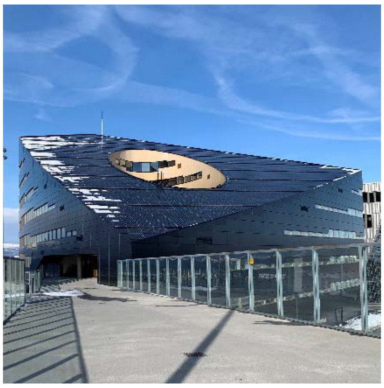
Façades
- Opaque surfaces
- Transparent surfaces
- Louvers
- Balconies

Roofs
- Flat
- Tilted
- Curved
- Other forms

Benefits

Examples

BIPV façade - Gioia 22, Milano (Italy)
Photo: M. Formolli



BIPV applied on façades and roof - Powerhouse Brattørkaia, Trondheim (Norway)
Photo: M. Formolli

Semi-transparent modules integrated into louvres - Le Albere, Trento (Italy)
Photo: S. Croce

Photovoltaic shelter - California Academy of Science, San Francisco (USA)
Photo: M. Formolli

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ST / BIST

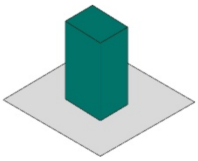
Solar thermal (ST) technologies harness solar energy and convert it into heat. Two main types of solar thermal collectors are diffused on the market:

- *Flat plate collectors* consist of a flat darkened absorbing plate, at the bottom of which pipes or channels are installed to transfer thermal energy to a working fluid (air, water or glycol mix). In glazed collector systems, the absorber is covered by transparent structures to allow solar penetration and limit both convection and radiation losses, and is insulated at the bottom to reduce conduction losses. Unglazed collector systems consist of an absorber without the glass covering and are often used for heating household swimming pools.
- *Evacuated tube collectors* consist of single tubes connected to a header pipe. Each tube is sealed to reduce heat losses of the water-bearing pipes to the ambient air. Evacuated tube collectors can have higher heat extraction efficiency compared to flat plate collectors in the temperature range above 80 °C, as they combine the effects of highly selective surface coating and vacuum insulation of the absorber element.

On building surfaces, ST collectors can also be integrated as part of a layer of the building envelope facing the surroundings. Such solutions, named *building-integrated solar thermal* (BIST) systems, include:

- Opaque BIST systems: solar thermal air collectors have been mainly developed to be integrated on roofs, in the form of flat systems or solar thermal tiles, and on façades or balcony railings.
- Semi-transparent BIST systems have also been developed for integrating solar energy production and visual comfort between the interior and the exterior of the building and heat generation. The solutions developed include, for example, semi-transparent façade collectors, fixed perforated horizontal slats attached to a pipe which can be mounted between glass panes, and semi-transparent absorbers with small slats and intermediate glass panes.

Suitable surfaces

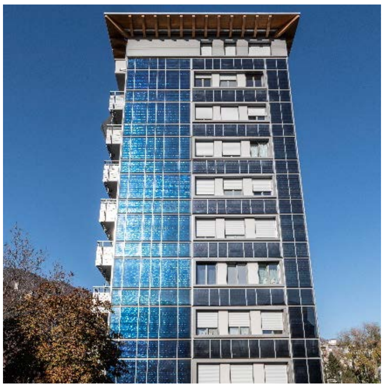


Façades
- Opaque surfaces
- Transparent surfaces
- Louvres
- Balconies

Roofs
- Flat
- Tilted

Benefits

Examples



BIST façade - Bolzano (Italy)
Photo: Ivo Corrá

Flat plate solar thermal collectors installed on the roof - Stadtwerk Lehnen, Salzburg (Austria)
Photo: Fotohof Phelbs

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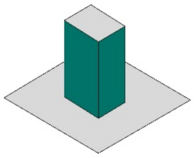
HYBRID PV/T SYSTEMS

Hybrid photovoltaic/Thermal systems (PV/T) combine energy generation with active heat recovery with liquid or forced air, in either a closed or open loop respectively.

- *Air cooled PV/T systems* consist of PV panels incorporated into a double-skin with a gap that allows air flow. In summer, the air flow can cool the PV modules; while, in winter, the system can pre-heat the air entering the building in combination with mechanical ventilation. The use of semi-transparent PV modules led to the further development of this technology as building integrated semi-transparent photovoltaic/thermal systems.
- *Water cooled PV/ST systems* consist of PV modules that are typically installed on the top of solar flat plate collectors. The presence of the collector aims to withdraw heat from the PV panels, improving its efficiency, and, at the same time, produces heated water for different purposes, such as domestic water, or space heating.

Suitable surfaces



Façades
- Opaque surfaces
- Balconies

Roofs
- Flat
- Tilted

Benefits

Examples

Experimental installation, photovoltaic-thermal solar panels for a solar-assisted heat pump. - Politecnico of Milan (Italy) Source: Wikimedia (Rich Schiz - licensed under CC-BY-SA 4.0)

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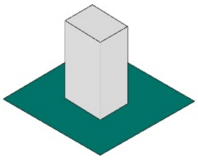
4.2.2 Energy systems for ground surfaces

SOLAR ENERGY SYSTEMS FOR GROUND SURFACES

On ground surfaces, the possibility of installing solar active energy system is investigated to increase the available area for power generation within the urban fabric.

- *Solar PV pavements and roads*: are proposed to replace traditional pavement materials. Several demonstration projects are being conducted to test different solutions. These include: bike paths with glass-coated PV panels, walkable solar-panelled pathways, and solar bricks which integrate LED illuminating devices. Beyond renewable energy generation, PV pavements have also been studied for their potential contribution to urban heat island (UHI) mitigation, showing a decrease of surface and ambient temperatures compared to conventional materials.
- *Asphalt solar collectors*: are constituted by a pipe system embedded in upper layers of the pavement; the solar energy absorbed by the pavement is transferred to the fluid within the pipes and used for heating applications. The harvested energy also contributes in cooling the pavement surface during hot periods; furthermore, the extracted heat can be used for melting the snow on roads and warm adjacent buildings.

Suitable surfaces



- Roads
- Cycle paths

Benefits

Examples

Portion of a solar powered road in Savoie Technolac science and technology park - Savoie (France) Source: Wikimedia (Florian Pépellin - licensed under CC-BY-SA 4.0)

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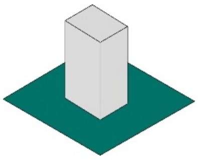
4.2.3 Energy systems for urban features

SOLAR ENERGY SYSTEMS FOR URBAN FEATURES

Other technologies for energy generation in urban areas exploit the surfaces of urban features, including:

- *acoustic PV road barriers*, which also serve the purpose of sound attenuation;
- *photovoltaic carports* on parking lots;
- *PV-integrated urban furniture*, such as street lighting, bus shelters, benches, etc.;
- *solar powered urban artworks*.

Suitable surfaces



- Urban furniture

Benefits

Examples

PV pergola - Violino photovoltaic village, Alessandria (Italy)
Source: Municipality of Alessandria

PV-integrated bench for the recharge of smartphones in a public squares - Sanremo (Italy)
Photo: S. Croce

Solar panel installation in front of the University of Applied Sciences - Zwickau (Germany)
Source: Wikimedia (André Karwath - licensed under CC BY-SA 2.5)

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4.3 Passive solar energy systems

Passive solar energy systems focus on exploiting direct interaction between the building envelope and the environment, in particular solar radiation. These strategies address the reduction of building's consumption for heating, cooling and lighting by preventing, collecting or controlling heat gains and natural lighting, without the use of electrical or mechanical equipment (Stevanović, 2013).

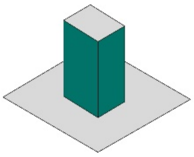
4.3.1 Passive solar heating

On the building surfaces, three major systems for passive solar heating strategies might be applied: i) direct gain through windows and glazed walls, ii) trombe walls, and iii) attached sunspaces / solar greenhouses.

WINDOWS / GLAZED WALLS & ROOFS

Windows and glazed walls designed with equator-facing orientation can act as direct-gain passive systems that allow solar radiation to enter the indoor spaces and be absorbed by the materials for later dissipation when the ambient temperature falls. In terms of spatial design, this is the most flexible passive solar strategy, as it allows integration of suitable daylight levels, aesthetic criteria, and the provision of heat. For an effective operation, the area of the windows should be designed taking into consideration both the area of thermal-storage materials within the indoor space, and the local climate characteristics to avoid daytime overheating.

Suitable surfaces



- Façades: transparent surfaces

Benefits

Examples

Glazed street - Skärholmen Centre, Stockholm (Sweden)
Source: M. Wall

Glazed courtyard - NTNU Elektrobygget, Trondheim (Norway)
Source: M. Formolli

References

Cuce, E. and Riffat, S. B. (2015) 'A state-of-the-art review on innovative glazing technologies', *Renewable and Sustainable Energy Reviews*. Elsevier, 41, pp. 695–714. doi: 10.1016/j.rser.2014.08.084.

Gupta, N. and Tiwari, G. N. (2016) 'Review of passive heating/cooling systems of buildings', *Energy Science and Engineering*, 4(5), pp. 305–333. doi: 10.1002/ese3.129.

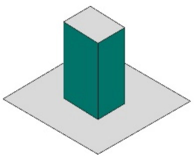
TROMBE WALLS

Trombe walls, also named thermal storage walls, are systems constituted by a dark-coloured equator facing heavy wall (i.e. made of masonry, concrete, bricks, etc.) with a double-glass system mounted on the outside and an insulating air-gap between the wall and the glazing. The solar radiation is absorbed by the dark surface on the outer face of the wall; the heat is transferred through the wall by conduction and then distributed to the indoor space by radiation and convection from the wall's inner surface. The glass system contributes by trapping the solar radiation re-emitted from the wall in the form of long-wave radiation between the glazing and the thermal mass. In a well-designed Trombe wall, thanks to the high heat capacity of the materials of the wall and the thickness of the wall, the heat gained during the day reaches the interior surface of the thermal mass by night time, warming the indoor spaces when most needed. Depending on the geographical location, it might be necessary to provide insulation and sufficient shade to the wall to minimise overheating during the warm season.

Beside classic Trombe walls, several types have been developed.

- *Composite Trombe wall*: consist of adding, on the inner side, a ventilated air layer and an insulation layer to the three classic layers (glazing, air layer, and storage layer of the thermal mass). In this configuration, the thermal energy transferred by conduction through the wall mass is then transferred by convection exploiting the thermos-circulation of air between the storage layer and the insulating wall. This design provides a greater thermal resistance than traditional configuration, hence minimizing the thermal flux from indoor to outdoor. Furthermore, the users can control the rate of heating by adjusting the air circulation.
- *Water Trombe wall*: uses water for heat storage instead of building materials.
- *Zigzag Trombe wall*: designed to reduce overheating and glare in hot sunny days. The wall is constituted by three sections: a southeast facing section with a window, providing heat and light in the morning, and a V shape with a classic Trombe wall, storing heat for redistribution during the night time.
- *Trans-wall system*: is a transparent modular wall that provides both heating and daylight. The system is constituted by two parallel glass panels, supported in a metal frame, enclosing water and a semi-transparent absorbing plate in-between. The incident solar radiation is partially absorbed by the water and by the plate, and the rest is transmitted to the indoor space, providing both heating and illumination.
- *PV Trombe wall*: integrates a PV coverage on the glazing, providing not only heat but also generating electricity.

Suitable surfaces



- Façades: opaque surfaces

Benefits

References

Gupta, N. and Tiwari, G. N. (2016) 'Review of passive heating/cooling systems of buildings', *Energy Science and Engineering*, 4(5), pp. 305–333. doi: 10.1002/ese3.129.

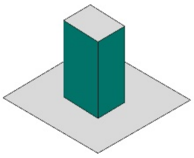
Hu, Z., He, W., Ji, J., & Zhang, S. (2017). A review on the application of Trombe wall system in buildings. *Renewable and Sustainable Energy Reviews*, 70(February 2016), 976–987. https://doi.org/10.1016/j.rser.2016.12.003

Saadatian, O., Sopian, K., Lim, C. H., Asim, N., & Sulaiman, M. Y. (2012). Trombe walls: A review of opportunities and challenges in research and development. *Renewable and Sustainable Energy Reviews*, 16(8), 6340–6351. https://doi.org/10.1016/j.rser.2012.06.032

SUNSPACES / SOLAR GREENHOUSES

Sunspaces or solar greenhouses are elements, usually with all the surfaces glazed, attached or integrated to the equator-facing side of the building. In such a way, an additional space, exposed to high solar radiation levels and a wide temperature range, is created. The wall dividing the sunspace from the rest of the building acts similarly to the Trombe wall. During wintertime, the greenhouse constitutes a buffer zone between the indoor spaces and the external environment, allowing the entrance of a large quantity of solar radiation. In summer, the space has to be equipped with shading devices or to be ventilated to avoid overheating.

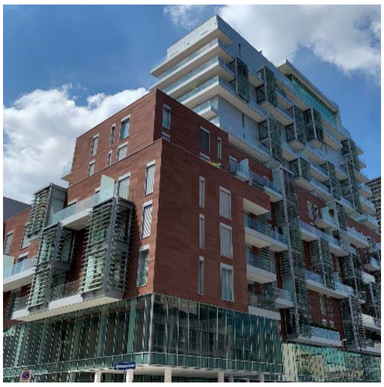
Suitable surfaces



- Façades: transparent surfaces

Benefits

Examples



Sunspaces in a residential building - Giardino d'inverno, Milan (Italy)
Photo: M. Formolli

Glazed verandas - Taberg (Sweden)
Source: M. Wall

References

Asdrubali, F., Cotana, F., & Messineo, A. (2012). ‘On the evaluation of solar greenhouse efficiency in building simulation during the heating period’. *Energies*, 5(6), 1864–1880. https://doi.org/10.3390/en5061864

Gupta, N. and Tiwari, G. N. (2016) ‘Review of passive heating/cooling systems of building’, *Energy Science and Engineering*, 4(5), pp. 305–333. doi: 10.1002/ese3.129.

Hestnes, A. G. (2000). ‘Building integration of solar energy systems’. *Solar Energy*, 67, 181–187.

4.3.2 Passive solar cooling

Passive cooling strategies aim at reducing energy consumption, protecting the environment and ecosystem, and providing satisfactory indoor comfort conditions (Bhamare, Rathod and Banerjee, 2019). These include

- heat protection techniques, which protect the building from direct solar heat gains;
- heat modulation techniques, which modulate heat gain by exploiting the thermal storage capacity of the building structure and materials;
- heat dissipation techniques, which dispose of the excess heat.

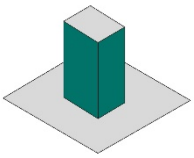
SHADING DEVICES

Shading is among the passive techniques that protect the building from direct solar radiation and heat gains, increasing the interior visual comfort and balancing the use of artificial light, while simultaneously reducing the cooling load. Solar shading systems provide significant control of visual and thermal conditions in indoor spaces. Such systems are among the most important bioclimatic strategies for building façades and include elements such as:

- *horizontal shading systems:* best suited for façades facing the equator, encompass overhangs, horizontal louvres, canopy, awnings, and light shelfs. The latter are horizontal surfaces designed to reflect natural daylight inside the building. On façades facing the sun, they reduce direct heat gains and glare, while simultaneously decreasing the need for artificial lighting;
- *blind systems*: window coverings made of various types of hard materials, which are used to control or block the access of daylight, and to reduce solar heat gains;
- *vertical shading systems*: best suited for façades facing east and west, encompass vertical louvres and projecting fins;
- *egg crate devices:* concrete grill blocks, metal grills, solar screens with geometrical perforations;
- *screenings*: venetian blinds, double glass windows, window quilt shade, movable insulation curtains, natural vegetation, etc.

Shading techniques can also be passive (i.e. not requiring any energy source for operation), which can be fixed or adjustable, active (i.e. relying on active energy for operation), and hybrid (i.e. utilizing advanced smart materials).

Suitable surfaces



Façades
- Transparent surfaces
- Opaque surfaces

Benefits

Examples

Vertical louvres applied on an office building - Vienna (Austria)
Photo: S. Croce

Horizontal louvres applied on a residential building - Lyon (France)
Photo: S. Croce

Circular egg crate shading devices - Jakarta (Indonesia)
Photo: S. Croce

References

Al-Masrani, S. M. et al. (2018) 'Design optimisation of solar shading systems for tropical office buildings: Challenges and future trends', *Solar Energy*. Elsevier, 170(April), pp. 849–872. doi: 10.1016/j.solener.2018.04.047.

Bhamare, D. K., Rathod, M. K., Banerjee, J. (2019), 'Passive cooling techniques for building and their applicability in different climatic zones—The state of art', *Energy and Buildings*, 198, pp. 467-490, doi: 10.1016/j.enbuild.2019.06.023.

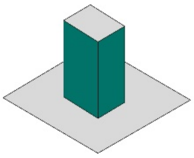
Gupta, N. and Tiwari, G. N. (2016) 'Review of passive heating/cooling systems of buildings', *Energy Science and Engineering*, 4(5), pp. 305–333. doi: 10.1002/ese3.129.

NATURAL VENTILATION

Natural ventilation is an efficient way to reduce energy consumption, as well as providing healthy indoor conditions.

- *Wind driven ventilation* delivers fresh air to indoor spaces without using any mechanical system, exploiting the difference in air temperature and pressure between indoor and outdoor. It is therefore important that the dimensions and location of the openings are correctly designed, taking into account the pressure and climatic parameters. Various devices are used for wind driven ventilation: wing walls, exhaust cowls, wind tower or wind catchers, and wind floor inlets.
- *Buoyancy driven ventilation*, also known as stack ventilation, is responsive to the vertical movement of air through the building thanks to buoyancy forces. Such forces arise due to density differences between warm and cool air, and discrepancies between indoor and outdoor air in terms of temperature and height. Buoyancy driven ventilation has several advantages, including the removal of hot air and the reduction of indoor temperature, providing fresh air from outside to inside, and pulling exhaust air out.

Suitable surfaces



Façades
- Transparent surfaces
- Opaque surfaces

Benefits

Examples

Wind tower - Dubai (United Arab Emirates)
Photo: M. Formolli

References

Aflaki, A. et al. (2015) ‘A review on natural ventilation applications through building façade components and ventilation openings in tropical climates’, *Energy and Buildings*, 101, pp. 153–162. doi: https://doi.org/10.1016/j.enbuild.2015.04.033.

Bhamare, D. K., Rathod, M. K., Banerjee, J. (2019), ‘Passive cooling techniques for building and their applicability in different climatic zones—The state of art’, *Energy and Buildings*, 198, pp. 467-490, doi: 10.1016/j.enbuild.2019.06.023.

Khan, N., Su, Y. and Riffat, S. B. (2008) ‘A review on wind driven ventilation techniques’, *Energy and Buildings*, 40(8), pp. 1586–1604. doi: 10.1016/j.enbuild.2008.02.015.

4.3.3 Daylight control

HELIOSTAT AND REFLECTOR SYSTEMS

Heliostats and reflector systems typically track the sun and redirect sunlight to surfaces that might otherwise be in shade. This is particularly important where urban densification restricts direct solar access and can be used to re-enliven spaces between buildings and within atrium spaces. This has been most notably demonstrated in the construction of One Central Park, Sydney Australia.

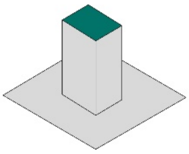
Dual-axis tracking heliostats mounted on a building rooftop redirects sunlight to the underside of a cantilevered reflector frame of fixed mirrors. Light is redirected into an atrium commercial retail space, a lap pool and park space that would otherwise be in shade. Green plantings in the indoor shopping centre depend upon the heliostat and reflector systems for essential growth.

The heliostats shown below are made of a plastic core and hail proof aluminium skin to provide a flat and rigid surface. This limits concentration of light and provides 75-80% of normal dispersed sunlight equating to around 800 watts/m^2 delivered to surfaces under clear sky conditions.

Besides heliostats, other means to actively capture solar light include:

- *light chimneys*, directing daylight trough a mirror tube and diffusing it indoor;
- *tubular skylights*, tube-shaped devices that capture sunlight through a rooftop lens and deliver it to the interior space thanks to a reflective-lined tube.

Suitable surfaces

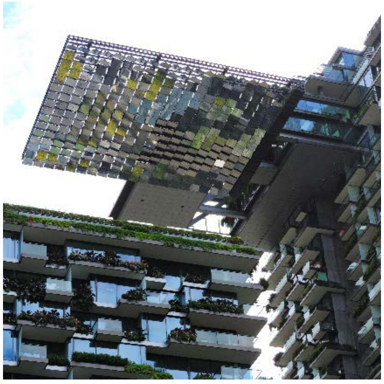


- Roofs: flat

Benefits

Examples

Heliostat mirror - One Central Park, Sydney (Australia)
Photo: M. Snow



Cantilevered reflector system - One Central Park, Sydney (Australia)
Photo: S. Croce

References

Atelier Jean Nouvel (2014) One Central Park. Available at: http://www.jeannouvel.com/en/projects/one-central-park/.

Frasers Property (2018) Central Park. Available at: http://www.frasersproperty.com/what-we-do/our-portfolio/aus_central-park-nsw.

PTW Architects. One Central Park. Available at: https://live.ptw.com.au/project/one-central-park.

Zaręba, A. et al. (2022) ‘Passive and Active Solar Systems in Eco-Architecture and Eco-Urban Planning’, Applied Sciences, 12(6), p. 3095. doi: 10.3390/app12063095.

4.4 Green solutions

Green solutions applied in urban areas have been classified into three major categories depending on the surfaces where they are applied in: i) vegetation on ground, ii) vegetated street furniture, and iii) green building elements.

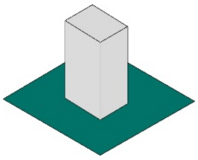
4.4.1 Vegetation on ground

AMENITY GREEN SPACES

Amenity green spaces encompass a great variety of solutions designed for both visual and recreational comfort. Among those:

- *urban parks*: green areas intended for recreational use by urban population;
- *botanical gardens*: areas with a large diversity of plant species with educational and ornamental purposes;
- *outdoor sport facilities*;
- *pocket parks*: publicly accessible small green areas situated around and between buildings.
- *semi-private or private green*, such as neighborhood green areas in multi-story residential zones, and house gardens located in close proximity to private buildings.

Suitable surfaces



- Public areas
- Urban parks
- Spaces in between buildings
- Brownfields

Benefits

Examples

Public urban park - Vienna (Austria)
Photo: S. Croce

Public urban park and outdoor sport facilities - Jakarta (Indonesia)
Photo: S. Croce

References

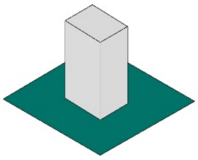
Chatzimentor, A., Apostolopoulou, E. and Mazaris, A. D. (2020) 'A review of green infrastructure research in Europe: Challenges and opportunities', *Landscape and Urban Planning*. Elsevier, 198(February), p. 103775. doi: 10.1016/j.landurbplan.2020.103775.

LINEAR GREEN SPACES

Green spaces defined by their linear features. Being located along the borders of the road networks or water bodies, linear green spaces include:

- *roadside planting*, i.e. street trees, hedges and shrubby or grassy verges planted along roads or other built-up elements;
- *riverbank green*;
- *vegetated railroad banks*;
- *green tramways*, created by replacing the sealed concrete surfaces of the tracks with vegetation, might offer space for additional greening, especially in dense built-up areas.

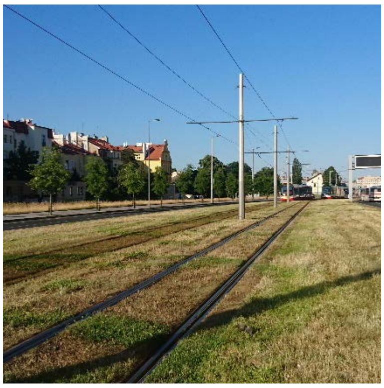
Suitable surfaces



- Roads
- Cycle paths
- Sidewalks
- Public areas
- Parking areas
- Rivers
- Lakes

Benefits

Examples



Green Tramway - Prague (Czech Republic)
Photo: S. Croce

Roadside planting - Vienna (Austria)
Photo: S. Croce

References

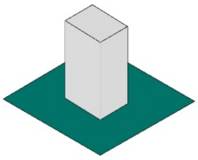
Sikorski, P. *et al.* (2018) 'Low-maintenance green tram tracks as a socially acceptable solution to greening a city', *Urban Forestry and Urban Greening*, 35(May), pp. 148–164. doi: 10.1016/j.ufug.2018.08.017.

FUNCTIONAL GREEN SPACES

Green spaces that serve a practical purpose, such as stormwater management, include:

- *raingardens*: shallow, vegetated areas able to collect and treat through infiltration the storm-water runoff from the surrounding impervious urban surface;
- *bioswales/biofilters*: vegetated elements designed to slow the speed of surface runoff and to allow stormwater infiltration and filtration to remove dissolved pollutants and particulate matter. They typically consist of shallow trenches, open channels or slopes containing a vegetated filter media; an underlying perforated pipe collects the treated water and delivers it to a drainage network or waterway.

Suitable surfaces

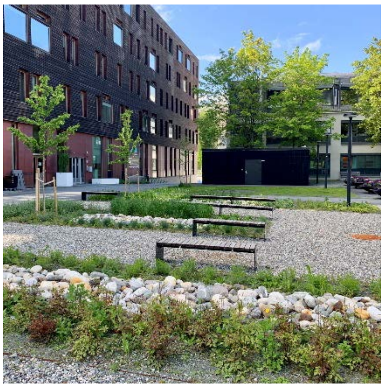


- Public areas
- Urban parks
- Spaces in between buildings

Benefits

Examples

Raingarden - Vienna (Austria)
Photo: S. Croce



Raingarden - ZEB building, Trondheim (Norway)
Photo: M. Formolli

References

Bortolini, L. and Zanin, G. (2018) ‘Hydrological behaviour of rain gardens and plant suitability: A study in the Veneto plain (north-eastern Italy) conditions’, *Urban Forestry and Urban Greening*. Elsevier, 34, pp. 121–133. doi: 10.1016/j.ufug.2018.06.007.

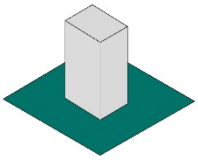
Hatt, B. E., Deletic, A. and Fletcher, T. D. (2007) ‘Stormwater reuse: designing biofiltration systems for reliable treatment’, *Water Science and Technology*, 55(4), pp. 201–209. doi: 10.2166/wst.2007.110.

Read, J. *et al.* (2008) ‘Variation among plant species in pollutant removal from stormwater in biofiltration systems’, *Water Research*, 42(4–5), pp. 893–902. doi: 10.1016/j.watres.2007.08.036.

TEMPORARY GREEN SPACES

The conversion of urban spaces into temporary green spaces for multifunctional uses is usually community based and aims at encouraging alternative and environmentally friendly uses of urban spaces. These approaches include the creation of urban gardens, community playgrounds, or *parklets*. The latter are bottom-up short term interventions launched in 2005 in San Francisco and have become a global phenomenon. Parklets temporarily transform on-street parking spaces into public spaces, by installing simple street furniture, which might include seats, vegetation, bike racks, or exercise equipment. The underlying aims are to encourage social interaction and people recreation, increase economic activity, and stimulate walking and cycling.

Suitable surfaces



- Roads
- Parking areas
- Brownfields

Benefits

Examples

Parklet, Łódź (Poland)
Source: Wikimedia (Zorro2212 - licensed under CC-BY-SA 4.0)

References

Cilliers, E. J. *et al.* (2015) 'Green Place-making in Practice: From Temporary Spaces to Permanent Places', *Journal of Urban Design*, 20(3), pp. 349–366. doi: 10.1080/13574809.2015.1031213.

Herman, K., Sbarcea, M. and Panagopoulos, T. (2018) 'Creating green space sustainability through low-budget and upcycling strategies', *Sustainability (Switzerland)*, 10(6), pp. 1–15. doi: 10.3390/su10061857.

Littke, H. (2016) 'Revisiting the San Francisco parklets problematizing publicness, parks, and transferability', *Urban Forestry and Urban Greening*. Elsevier GmbH., 15, pp. 165–173. doi: 10.1016/j.ufug.2015.12.010.

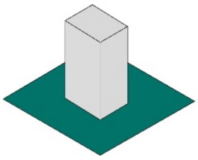
4.4.2 Vegetated street furniture

Street furniture systems integrating vegetated solutions have been developed to supplement the existing vegetation in urban areas, especially for air pollutants removal, and improvement of urban biodiversity.

VERTICAL PLANTING SYSTEMS

Innovative vertical planting systems, integrate vegetation and Internet of Things (IoT) technology in elements to be deployed in urban areas.

An example is the CityTree, a stand-alone independent vertical planting system that can be easily placed in an urban location. The vertical system is constituted by a moss substrate hosting vascular plants. It is complemented with a wooden bench, and hosts built-in sensors to monitor both its environmental performance and conditions.

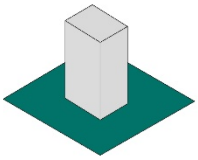
Suitable surfaces		- Urban furniture
Benefits		
Examples	 *CityTree system - Glasgow (Scotland) Source: Wikimedia (Rosser1954 - licensed under CC-BY-SA 4.0)*	
References	greencity solutions (2020) *The world's first bio-tech filter to quantifiably improve air quality*. Available at: https://greencitysolutions.de/en/solutions/ Sänger, P. and Splittgerber, V. (2016) 'The Citytree: A vertical plant filter for enhanced temperature management', in Leal Filho, W. (ed.) *Innovation in Climate Change Adaptation*. Hamburg: Springer, pp. 131–144. doi: 10.1007/978-3-319-25814-0.	

VEGETATED PERGOLAS AND BUS STOPS

The integration of vegetation in the street furniture include:

- *Vegetated pergolas*, created using ropes and greenery to generate different thermal comfort and lighting conditions depending on the season, as deciduous plants are often used.
- *Eco-friendly bus stops*, featuring a green roof. The shelters support biodiversity, providing habitat for bees, while producing other positive environmental effects, such as air quality improvement, rainwater absorption, and temperatures regulation. An example of implementation can be found in Utrecht (Netherlands), where low-maintenance sedum-covered roofs have been installed on 316 bus stops.

Suitable surfaces



- Urban furniture

Benefits

Examples

Vegetated bus stop - Norwich (United Kingdom)
Source: Wikimedia (Northmetpit - licensed under CC-BY-SA 4.0)

References

Alexandri, E. and Jones, P. (2006) 'Ponds, green roofs, pergolas and high albedo materials; which cooling technique for urban spaces?', *PLEA 2006 - 23rd International Conference on Passive and Low Energy Architecture, Conference Proceedings*, (March 2015).

Chàfer, M. *et al.* (2020) 'Greenery system for cooling down outdoor spaces: Results of an experimental study', *Sustainability (Switzerland)*, 12(15). doi: 10.3390/SU12155888.

Hirsh, S. (2019) *These bus stops are a sanctuary for bees*, *World Economic Forum*. Available at: https://www.weforum.org/agenda/2019/07/bees-can-take-refuge-on-these-bus-stop-green-roofs.

4.4.3 Green building elements

Green building elements include solutions for greening the surfaces of buildings, both roofs and façades.

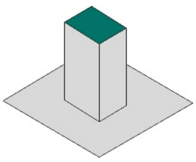
HORIZONTAL GREENING SYSTEMS

Horizontal greening systems are constituted by different layers to provide the growing conditions for vegetation on flat or sloped rooftop surfaces. Depending on the type of use and vegetation, and the maintenance requirements, such systems can be categorized into three major groups:

- *Extensive green roofs*: are characterized by a thin layer of growing medium (i.e. thickness around 6–20 cm), on which only herbs and grass are grown. This solution requires low maintenance and only periodical irrigation, is lightweight and is suitable for both flat and tilted roofs. Due to the limited soil depth and vegetation, extensive green roofs have a relatively low stormwater management potential and energy performance.
- *Intensive green roofs*: are designed with a considerable layer of growing medium (i.e. more than 20, up to 100 cm), which allows to plant also perennials, shrubs and trees, hence requiring permanent maintenance and irrigation. The variety of vegetation allows the creation of a natural environment able to improve biodiversity and to provide a recreational space, as these types of roofs are usually accessible by humans. Due to the heavy weight (180-500 kg/m^2), intensive solutions are only suitable for flat rooftop surfaces, or roofs with a slope lower than 10°. Intensive green roofs have a high water retention capacity (over 50%); hence, they have a better stormwater management potential than extensive green roofs, reducing runoff up to 85% compared to traditional roofing systems.
- *Semi-intensive green roofs*: present a combination of the two previous types, with a typical depth of the growing medium from 15 to 30 cm. These systems are characterised by herbaceous plants and small shrubs, requiring moderate maintenance and occasional irrigation.

Ongoing research is also evaluating the potential of *moss greening systems* as an affordable solution for the building envelope. Indeed, the low ecological needs of mosses in terms of growing substrates, and amount of water and nutrients required allows their survival also in unfavourable environmental conditions. For this reason and its ability of growing directly on common building materials, the use of moss on building surfaces is being tested for the implementation and diffusion of single layer low-cost solutions.

Suitable surfaces



Roofs:

- Flat
- Tilted
- Curved
- Other forms

Benefits

Examples

Extensive green roof, Bolzano (Italy)
Photo: S. Croce

Traditional green roof, Røros (Norway)
Photo: M. Formolli

References

Cascone, S. (2019) 'Green roof design: State of the art on technology and materials', *Sustainability (Switzerland)*, 11(11). doi: 10.3390/su11113020.

Kaufman, M. A. (2016) 'A Feasibility Growth Study of Native Mosses Associated with Self-Sustaining Flora on Vertical Infrastructure', in *International Conference on Transportation and Development 2016 : Projects and Practices for Prosperity*. doi: 10.1061/9780784479926.063.

Mayrand, F. and Clergeau, P. (2018) 'Green roofs and greenwalls for biodiversity conservation: A contribution to urban connectivity?', *Sustainability (Switzerland)*, 10(4). doi: 10.3390/su10040985.

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Perini, K. *et al.* (2020) 'Experiencing innovative biomaterials for buildings: Potentialities of mosses', *Building and Environment*. Elsevier Ltd, 172(November 2019), p. 106708. doi: 10.1016/j.buildenv.2020.106708.

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VERTICAL GREENING SYSTEMS

Vertical greenery systems include all those techniques that enable growing plants on, up, or within the walls of a building, which can be classified into two main groups:

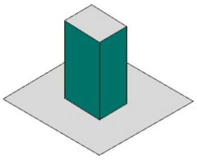
- *Green façades*: are based on the use of wall surfaces for climbing or hanging plants along them with low systemic technology. These systems are characterized by a low the level of integration between plants and walls, and can also be used on transparent surfaces for shading purposes. They can be differentiated into direct or indirect, respectively when the plants are directly attached to the wall, or their growth is supported by a structural system.
- *Living walls*: are characterised by a more complex structure, which includes supporting elements, growing media and irrigation systems and allows a more uniform growth of the vegetation along the vertical surface. Two methods exist for the application of the vegetation; plants can grow in lightweight felt layers without requiring a soil substrate (i.e. continuous living walls), or in panels constituted by specific supporting elements (i.e. modular living walls). Due to the technical requirements, living walls can cover only the opaque area of the façades.

Also in the case of vertical surfaces, *moss greening systems* can be applied. Further solutions for the greening of building façades include the design of a *movable green window shading system*, composed by a sliding planting module that can be moved for switching from shaded to un-shaded conditions.

New innovative green technological solutions are being developed for building surfaces; in particular, a new concrete material able to host plants to allow a cast-in-place system for living walls in new constructions is being developed and tested. The *vertically-cast pervious concrete* allows to grow plants from seeds directly in-situ, without the need to raise and transplant nursery plants.

Finally, balconies of individual buildings, mainly residential ones, might also offer the space for growing vegetation in *balcony gardens*.

Suitable surfaces



Façades

- Opaque surfaces
- Transparent surfaces

Benefits

Green façades - Living walls

Balcony gardens

Examples

Living wall - Sidney (Australia)
Photo: S. Croce

Balcony gardens - Bosco Verticale, Milano (Italy)
Photo: M. Paparella

References

Manso, M. and Castro-Gomes, J. (2015) 'Green wall systems: A review of their characteristics', *Renewable and Sustainable Energy Reviews*. Elsevier, 41, pp. 863–871. doi: 10.1016/j.rser.2014.07.203.

Pérez, G. *et al.* (2014) 'Vertical Greenery Systems (VGS) for energy saving in buildings: A review', *Renewable and Sustainable Energy Reviews*. Elsevier, 39, pp. 139–165. doi: 10.1016/j.rser.2014.07.055.

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Zheng, X., Dai, T. and Tang, M. (2020) 'An experimental study of vertical greenery systems for window shading for energy saving in summer', *Journal of Cleaner Production*. Elsevier Ltd, 259, p. 120708. doi: 10.1016/j.jclepro.2020.120708.

4.5 Water solutions

Water solutions include the following main sub-categories: water surfaces, evaporative techniques, and water squares.

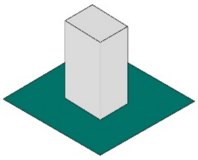
4.5.1 Water surfaces

WATER SURFACES

The presence of water in urban areas occurs typically in:

- *natural water bodies* such as ponds, lakes, rivers and canals;
- *artificial water surfaces*, which comprise fountains, artificial lakes and other man-made urban features, such as systems designed to manage on-site storm-water quantity and quality. The latter include retention and detention basins, which are man-made ponds designed to intercept the water runoff during extreme storm events to attenuate the peak flow.
- *deculverted waterways*, i.e. urban watercourses previously buried to create roads and built-up areas, which have been reopened and restored to natural conditions. Deculverting actions are mainly conducted to tackle problems associated with buried canals and rivers, such as flooding, water pollution, and habitat loss, but also provide social and economic impacts by offering recreation for local communities and an incentive for regeneration.

Suitable surfaces



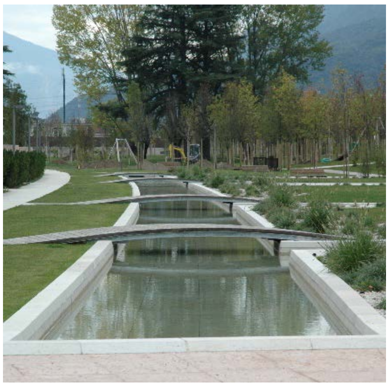
- Urban parks
- Rivers
- Lakes

Benefits

Natural water bodies

Artificial water surfaces
Deculverted watereways

Examples



Artificial water surface - Trento (Italy)
Photo: S. Croce

Urban canal - Mantova (Italy)
Photo: S. Croce

References

Park, D., Jang, S. and Roesner, L. A. (2014) 'Evaluation of multi-use stormwater detention basins for improved urban watershed management', *Hydrological Processes*, 28(3), pp. 1104–1113. doi: 10.1002/hyp.9658.

Shooshtarian, S., Rajagopalan, P. and Sagoo, A. (2018) 'A comprehensive review of thermal adaptive strategies in outdoor spaces', *Sustainable Cities and Society*. Elsevier, 41(February), pp. 647–665. doi: 10.1016/j.scs.2018.06.005.

Wild, T. C. *et al.* (2011) 'Deculverting: Reviewing the evidence on the "daylighting" and restoration of culverted rivers', *Water and Environment Journal*, 25(3), pp. 412–421. doi: 10.1111/j.1747-6593.2010.00236.x.

4.5.2 Evaporative techniques

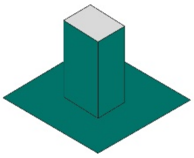
Apart from water bodies, various techniques based on the evaporation of water are available in cities, mainly with the aim to reduce the ambient temperature. These include water systems like mist spraying and water curtains, and watering techniques (Santamouris *et al.*, 2016).

MIST SPRAYING AND WATER CURTAINS

Systems supplying water directly in the air can be particularly efficient for improving the thermal comfort in outdoor urban environments due to the proximity to individuals benefiting from the cooling. These include:

- *mist spray systems*, constituted by nozzles producing a cloud of fine droplets that increase the surface contact area between air and water resulting in a higher evaporation yield and consequent ambient air cooling.
- *water curtains*, often integrated outside large glazed building surfaces for reducing both the outdoor air temperature and the incoming solar radiation in the interior spaces.

Suitable surfaces



- Sidewalks
- Public areas
- Urban parks
- Façades: transparent surfaces
- Open atria
- Courtyards

Benefits

Examples

Mist spraying system - Prague (Czech Republic)
Photo: S. Croce

References

Guo, P. *et al.* (2019) 'Research on Landscape Energy-Saving Integrated Water Curtain System', *Journal of Thermal Science*, 28(6), pp. 1150–1163. doi: 10.1007/s11630-019-1239-9.

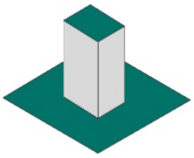
Santamouris, M. *et al.* (2016) 'Passive and active cooling for the outdoor built environment - Analysis and assessment of the cooling potential of mitigation technologies using performance data from 220 large scale projects', *Solar Energy*. Elsevier Ltd. doi: 10.1016/j.solener.2016.12.006.

Ulpiani, G. *et al.* (2019) 'Thermal comfort improvement in urban spaces with water spray systems: Field measurements and survey', *Building and Environment*. Elsevier, 156(February), pp. 46–61. doi: 10.1016/j.buildenv.2019.04.007.

WATERING TECHNIQUES

Watering techniques consist of spreading water over urban surfaces or building façades mainly for reducing temperatures in urban areas. Furthermore, in the case of ground surfaces, such solution may also be used for placating dust particles on the ground. Several methods have been proposed, both for vertical surfaces, and mainly for pavements and ground surfaces. Solutions are also available for evaporative cooling over roof surfaces; these include water spraying, in which sprinkler systems are used to reduce roof's surface temperature, and roof ponds, making advantage of the increased heat capacity of water.

Suitable surfaces



- Roads
- Sidewalks
- Cycle paths
- Public areas
- Roofs: flat

Benefits

References

Daniel, M., Lemonsu, A. and Viguié, V. (2018) 'Role of watering practices in large-scale urban planning strategies to face the heat-wave risk in future climate', *Urban Climate*. Elsevier B.V., 23, pp. 287–308. doi: 10.1016/j.uclim.2016.11.001.

He, J. and Hoyano, A. (2008) 'A numerical simulation method for analyzing the thermal improvement effect of super-hydrophilic photocatalyst-coated building surfaces with water film on the urban/built environment', *Energy and Buildings*, 40(6), pp. 968–978. doi: 10.1016/j.enbuild.2007.08.003.

Hendel, M. *et al.* (2016) 'Measuring the effects of urban heat island mitigation techniques in the field: Application to the case of pavement-watering in Paris', *Urban Climate*. Elsevier B.V., 16, pp. 43–58. doi: 10.1016/j.uclim.2016.02.003.

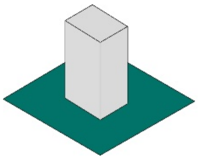
Spanaki, A., Tsoutsos, T. and Kolokotsa, D. (2011) 'On the selection and design of the proper roof pond variant for passive cooling purposes', *Renewable and Sustainable Energy Reviews*. Elsevier Ltd, 15(8), pp. 3523–3533. doi: 10.1016/j.rser.2011.05.007.

Tiwari, G. N., Kumar, A. and Sodha, M. S. (1982) 'A review-Cooling by water evaporation over roof', *Energy Conversion and Management*, 22(2), pp. 143–153. doi: 10.1016/0196-8904(82)90036-X.

4.5.3 Water squares

WATER SQUARES

Water squares are multi-functional non-vegetated solutions that combine their use as public spaces in regular climatic conditions (e.g. playing grounds, skate parks, etc.), with their function as temporary rainwater storage in case of downpours. These squares are composed of one or more paved lower-lying areas, which, during intense rain events, constitute aboveground basins that can retain rainwater from the surrounding district until the city sewage systems can manage its discharge.

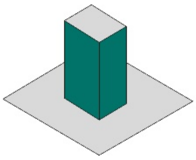
Suitable surfaces		- Public areas
Benefits		
Examples	 *Benthemplein water square - Rotterdam (Netherlands)* *Source: Wikimedia (Cathrotterdam - licensed under CC-BY-SA 4.0)*	
References	Ilgen, S., Sengers, F. and Wardekker, A. (2019) 'City-To-City Learning for Urban Resilience: The Case of Water Squares in Rotterdam and Mexico City', *Water*, 11(5), p. 983. doi: 10.3390/w11050983. Perini, K. (2017) 'Green and Blue Infrastructure – Unvegetated Systems', in Perini, K. and Sabbion, P. (eds) *Urban Sustainability and River Restoration: Green and Blue Infrastructure*. John Wiley & Sons Ltd., pp. 63–75.	

4.5.4 Water solutions for building envelope

WATER HARVESTING FAÇADES

Various factors such as roof materials, geometry, surrounding households and neighborhood conditions can significantly affect the quality of rainwater and its harvesting, for household consumption. For outdoor utilization purposes, rainwater harvesting through residential rooftops provide significant opportunity to satisfy the demand even in low rainfall zones. Rainwater Harvesting (RWH) systems might be more economically feasible on a neighborhood scale employing different urban surfaces such as pavements. At small scale or household scale, water purification quality would not be maintained and, from life cycle perspective, the decentralized water harvesting system is more expensive than a centralized system for household purposes.

Suitable surfaces



Façades

- Opaque surfaces
- Transparent surfaces

Benefits

References

Norman, M., Shafri, H.Z., Mansor, S.B. and Yusuf, B., 2019. Review of remote sensing and geospatial technologies in estimating rooftop rainwater harvesting (RRWH) quality. International soil and water conservation research, 7(3), pp.266-274.

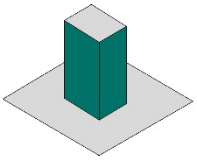
Tamaddun, K., Kalra, A. and Ahmad, S., 2018. Potential of rooftop rainwater harvesting to meet outdoor water demand in arid regions. Journal of Arid Land, 10(1), pp.68-83.

Hofman-Caris, R., Bertelkamp, C., de Waal, L., van den Brand, T., Hofman, J., van der Aa, R. and van der Hoek, J.P., 2019. Rainwater harvesting for drinking water production: a sustainable and cost-effective solution in the Netherlands?. Water, 11(3), p.511.

WATER WALLS FOR THERMAL MASS

Various materials are being tested as a means of replacing the thick thermal mass wall. Water has been found to be better for indirect heat gain than masonry and so has the potential to be an upgrade in colder climates. Although the water surface temperature does not become as hot as masonry, this helps to reduce the amount of heat that is lost back through the glazing. It also has the ability to store more energy than most other materials because of its high specific heat capacity. Similar to a thermal mass wall, water uses conduction to distribute its heat from the inside surface to the outside surface of its container and then out into the conditioned space through radiation. It was also shown that a thicker water wall would help to maintain cooler temperatures inside the building than a thinner water wall would. Of course, water is hard to contain which may result in more complications relative to the ease of a classic Trombe wall.

Suitable surfaces



Façades
- Opaque surfaces
- Transparent surfaces

Benefits

References

Saadatian O, Sopian K, Lim CH, Asim N, Sulaiman MY. Trombe walls: A review of opportunities and challenges in research. Renewable and Sustainable Energy Reviews. 2012;16:6340-6351.

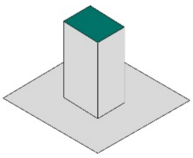
ROOF PONDS

Roof ponds make use of water as ideal thermal mass, due to its high volumetric heat capacity, to provide passive heating and cooling. During daytime hours, the heat gained from solar irradiation is partially absorbed and stored by the water. In this way, the appearance of the indoor peak temperature is delayed to the late afternoon, when the ambient temperature is already lower. During night, the pond is cooled by radiant cooling.

Different types of roof ponds have been applied on buildings; the most common types include:

- *Open roof ponds*, usually supported by flat concrete slabs, are constituted by a body of water (minimum depth 30 cm) exposed to the ambient environment. These systems also provide evaporative cooling, and can be with or without sprays. In the first case, water is sprayed on the roof during the day, increasing both heat absorption and evaporative cooling.
- *Roof ponds with movable insulation* integrate insulation panels made of highly reflective opaque materials. The panels prevent the overheating of water during daytime, and are removed at night-time to facilitate radiative cooling.
- *Ventilated roof ponds* consist of a roof pond placed over an either concrete or metallic roof slab, covered by a permanent insulation layer, made of highly reflective metallic sheets over insulating materials. A ventilated air layer separated the insulation from the water surfaces. In this system, cooling is achieved only through convection and evaporation. During winter, the water is drained and the vents are closed to prevent excessive heat loss and provide an additional insulation layer. An advantage of this solution is the potential application also on non-flat roofs.

Suitable surfaces



- Roofs: flat

Benefits

References

Bhamare, D. K., Rathod, M. K., Banerjee, J. (2019), 'Passive cooling techniques for building and their applicability in different climatic zones—The state of art', *Energy and Buildings*, 198, pp. 467-490, doi: 10.1016/j.enbuild.2019.06.023.

Sharifi, A. and Yamagata, Y. (2015) 'Roof ponds as passive heating and cooling systems: A systematic review', *Applied Energy*. Elsevier Ltd, 160, pp. 336–357. doi: 10.1016/j.apenergy.2015.09.061.

4.6 Urban agriculture

Urban agriculture, i.e. the practice of growing food, within cities, embraces several approaches, including ground-based farming, building-integrated agriculture, as well as other practices (Azunre *et al.*, 2019).

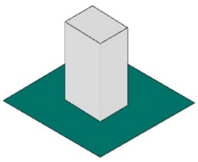
4.6.1 Ground-based farming

GROUND-BASED FARMING

Ground-based farming is the most traditional form of urban agriculture. It includes different practices, depending on the size and ownership of the urban surfaces on which it is operated:

- *backyard gardens*: privately cultivated by the building owners;
- *community gardens*: collectively organized open spaces operated by the local community;
- *urban micro-farms / urban farms*: operated for profit. The first are small in scale and low-tech, and are closely linked by the presence of schemes for community support or local farmer markets. On the contrary, urban farms are bigger in scale and operated for commercial purposes;
- *urban orchards*: production systems based on fruit trees, which is becoming increasingly common in schools and hospitals open spaces.

Suitable surfaces



- Public areas
- Spaces in-between buildings
- Brownfields

Benefits

Examples

Community gardens - Carpi (Italy)
Photo: M. Formolli

References

Guitart, D., Pickering, C. and Byrne, J. (2012) 'Past results and future directions in urban community gardens research', *Urban Forestry and Urban Greening*. Elsevier GmbH., 11(4), pp. 364–373. doi: 10.1016/j.ufug.2012.06.007.

Lin, B. B. *et al.* (2017) 'Urban Agriculture as a Productive Green Infrastructure for Environmental and Social Well-Being', in Tan, P. Y. and Jim, C. Y. (eds) *Greening cities. Form and functions*. Springer, pp. 155–179.

O'Sullivan, C. A. *et al.* (2019) 'Strategies to improve the productivity, product diversity and profitability of urban agriculture', *Agricultural Systems*. Elsevier, 174(May), pp. 133–144. doi: 10.1016/j.agsy.2019.05.007.

Skar, S. L. G. *et al.* (2020) 'Urban agriculture as a keystone contribution towards securing sustainable and healthy development for cities in the future', *Blue-Green Systems*, 2(1), pp. 1–27. doi: 10.2166/bgs.2019.931.

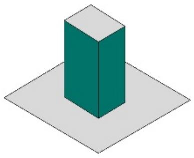
4.6.2 Building-integrated agriculture

Building-integrated agriculture encompasses all the farming practices adapted for the surfaces of the building envelope or its interior (Caplow and Nelkin, 2007). Such methods exploits the synergies between farming technologies and built environment, providing benefits such as decreased water use, more efficient waste management cycles and building-integrated renewable energy sources (Benis, Reinhart and Ferrão, 2017).

EDIBLE GREEN WALLS

Green walls can also produce food as a provisioning ecosystem service. To this aim, edible walls include agricultural practices on vertical greening systems on buildings.

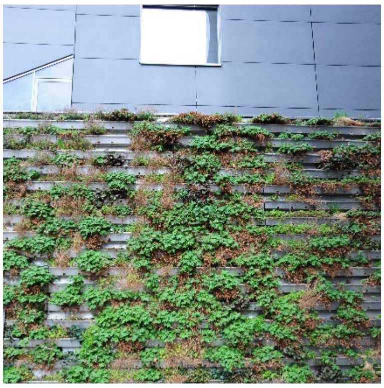
Suitable surfaces



- Façades: opaque surfaces

Benefits

Examples



Edible wall - Vienna (Austria)
Photo: S. Croce

References

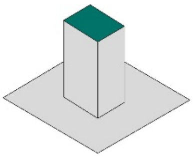
Russo, A. *et al.* (2017) 'Edible green infrastructure: An approach and review of provisioning ecosystem services and disservices in urban environments', *Agriculture, Ecosystems and Environment*. Elsevier, 242(March), pp. 53–66. doi: 10.1016/j.agee.2017.03.026.

ROOFTOP FARMING

Rooftop farming occupy otherwise often unused space in the built environment, overcoming some of the major limits for in-ground agriculture, i.e. limited space and competitive real-estate market. It includes:

- *open-air rooftop farms*: soil-based farms operated on green roof technologies
- *rooftop greenhouses*: could achieve higher performance than traditional rooftop farming in terms of yield, efficiency of water use and stormwater retention. Usually, rooftop greenhouses utilize hydroponic soilless culture methods that do not necessitate any significant structural reinforcement of the buildings to operate.

Suitable surfaces



- Roofs: flat

Benefits

Open-air rooftop farming

Rooftop greenhouses

Examples

Brooklyn Grange rooftop farm - New York (USA)
Source: Wikimedia (Ian Bartlett - licensed under CC-BY-SA 4.0)

References

Buehler, D. and Junge, R. (2016) ‘Global trends and current status of commercial urban rooftop farming’, *Sustainability (Switzerland)*, 8(11), pp. 1–16. doi: 10.3390/su8111108.

Harada, Y. and Whitlow, T. H. (2020) ‘Urban Rooftop Agriculture: Challenges to Science and Practice’, *Frontiers in Sustainable Food Systems*, 4(June), pp. 1–8. doi: 10.3389/fsufs.2020.00076.

Orsini, F. *et al.* (2017) *Urban Agriculture: Rooftop Urban Agriculture*. Springer.

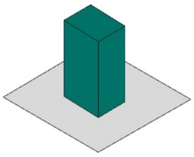
4.6.3 Other forms of urban agriculture

HYDROPONICS

Hydroponics is an agricultural method without soil, which uses mineral nutrient solutions in water for crops production; it is a widespread technology in vertical farming and rooftop greenhouses production, but can also be applied in other contexts. Compared to traditional farms, hydroponics reduces water needs - up to 90% - and the cultivation space for plant growth, minimizes health risks, and controls environmental contamination.

In urban areas, hydroponics can play an important role in environmental regulation; in arid climates it increases humidity levels and decreases temperatures. It also contributes to the capture of dust and polluted air and to the reduction of the overall discharge of CO_2. When applied on buildings, hydroponic systems contribute to their thermoregulation.

Suitable surfaces



- Façades: opaque surfaces
- Roofs: flat

Benefits

Examples

Hydroponic cultivation
Source Wikimedia (Oregon State University - licensed under CC-BY-SA 2.0)

References

Romeo, D., Vea, E. B. and Thomsen, M. (2018) 'Environmental Impacts of Urban Hydroponics in Europe: A Case Study in Lyon', *Procedia CIRP*. The Author(s), 69(May), pp. 540–545. doi: 10.1016/j.procir.2017.11.048.

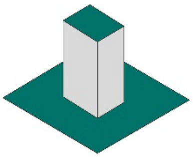
Schnitzler, W. H. (2013) 'Urban hydroponics for green and clean cities and for food security', *Acta Horticulturae*, 1004(May 2012), pp. 13–26. doi: 10.17660/ActaHortic.2013.1004.1.

AQUACULTURE AND AQUAPONICS

Food production methods that require the use of water and might also be applied in urban areas include:

- *aquaculture*: practice of farming fish. Urban aquaculture systems include tanks, ponds, lakes and reservoirs, and peri-urban wetlands.
- *aquaponics*: integration of aquaculture and hydroponic into a bio-system that creates a symbiotic relationship between fish and plants. This symbiosis is achieved by using the nutrient-rich waste from fish tanks to fertilize the hydroponic production beds. In turn, the latter also function as bio-filters removing from the water gases, acids, and chemicals.

Suitable surfaces



- Lakes
- Rivers
- Roofs: flat

Benefits

Examples

Aquaponic system for the production of fish, watercress and tomatoes – Growing Power, Milwaukee (USA) Source: Wikimedia (ryan griffis - licensed under CC BY-SA 2.0)

References

Al-Kodmany, K. (2018) 'The Vertical Farm: A Review of Developments and Implications for the Vertical City', *Buildings*, 8(2), p. 24. doi: 10.3390/buildings8020024.

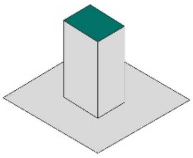
Bunting, S. W. and Little, D. C. (2015) 'Urban aquaculture for resilient food systems', in de Zeeuw, H. and Drechsel, P. (eds) *Cities and Agriculture - Developing Resilient Urban Food Systems*. Routledge, pp. 312–335.

dos Santos, M. J. P. L. (2016) 'Smart cities and urban areas—Aquaponics as innovative urban agriculture', *Urban Forestry and Urban Greening*. Elsevier GmbH., 20, pp. 402–406. doi: 10.1016/j.ufug.2016.10.004.

APICULTURE

Urban beekeeping had a boom in popularity over the last decade in built-up areas as a response to the honeybee decline threatening pollination levels in agriculture and ecosystems.

Suitable surfaces



- Urban parks
- Spaces in-between buildings
- Roofs: flat

Benefits

Examples

Bee-hive on an extensive green roof - Bolzano (Italy)
Photo: S. Croce

References

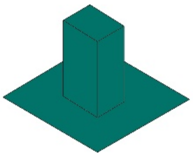
Lorenz, S. and Stark, K. (2015) 'Saving the honeybees in Berlin? A case study of the urban beekeeping boom', *Environmental Sociology*, 1(2), pp. 116–126. doi: https://doi.org/10.1080/23251042.2015.1008383.

MICROALGAE-BASED BIOMIMICRY

The urban cultivation of microalgae has attracted increasing interest due to their potential for food resources production. Microalgae cultivation can be realized in open-air systems, such as ponds, or in closed system such as photo-bioreactors.

Several initiatives are aimed at developing building-integrated solutions or making use of infrastructure and rooftop spaces. Examples include the *BioSolar Leaf* solution, where microalgae are cultivated in solar panel-like structures that can be installed on land or buildings. This solution aims at improving air quality in urban areas, as the cultivation system can remove carbon dioxide and produce oxygen, and at producing organic biomass from which nutritious food additives for plant-based food products are extracted. *PhotoSynthetica* is a building cladding system made of custom-made bioplastic containers incorporating living micro-algal cultures, which make use of solar energy to remove greenhouse gases and pollutants from the atmosphere, and to produce a food resource in the form of algae.

Suitable surfaces



- Lakes
- Façades: opaque and transparent surface
- Roofs: flat

Benefits

Examples

Tubular glass photobioreactor for the cultivation of microalgae
Source: Wikimedia (IGV Biotech - licensed under CC BY-SA 3.0)

References

Arborea (2019) *BioSolar Leaf*. Available at: http://arborea.io/

Barsanti, L. and Gualtieri, P. (2018) 'Is exploitation of microalgae economically and energetically sustainable?', *Algal Research*. Elsevier, 31(October 2017), pp. 107–115. doi: 10.1016/j.algal.2018.02.001.

ecoLogicStudio (2019) *photo.Synthetica*. Available at: https://www.photosynthetica.co.uk/system (Accessed: 10 February 2020).

Evanson, D. (2019) 'World's first "BioSolar Leaf" to tackle air pollution in White City', *Imperial College London*, April. Available at: https://www.imperial.ac.uk/news/191026/worlds-first-biosolar-leaf-tackle-pollution/.

4.7 Cool materials and innovative solutions

Cool materials and innovative solutions include all those urban materials or paintings able to maintain lower surface temperatures compared to traditional ones, by absorbing and storing reduced quantities of solar radiation (Croce and Vettorato, 2021).

4.7.1 Highly reflective and emissive materials

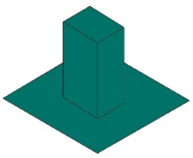
HIGHLY REFLECTIVE AND EMISSIVE MATERIALS

The most popular cool materials are characterized by high solar reflectivity (i.e. ability of a material to reflect solar radiation) and high infrared emissivity (i.e. ability of a surface to release absorbed heat). These characteristics help decreasing urban surface temperature, reducing the corresponding release of sensible heat to the atmosphere, and mitigating the UHI. The cool materials were originally designed to be *white or light-colored*, and highly-reflective in the visible wavelength. Successive scientific developments have led to materials, which absorb in the visible part of the radiation spectrum, hence appearing to have a *specific color*, and are highly reflective in the near-infrared spectrum.

Cool materials can be used either on the building envelope or on ground surfaces.

- On ground surfaces, cool pavements include a range of materials and techniques, such as the use of white or light-colored aggregates or overlaying layers over asphalt and concrete surfaces. Increasing the solar reflectance of pavements can potentially result in glare problems or in uncomfortable human thermal comfort conditions in areas where people may be exposed to the reflected radiation. For these reasons, cool colored pavement solutions have also been developed.
- On the building envelope, white or light-colored materials are usually applied on horizontal surfaces or with a low slope, such as flat roofs, to avoid glare problems; while, on more visible surfaces and on roofs with steep slope, colored materials are more diffused in order to both obtain enhanced solar reflectance and meet the requirements of architectural integration. Cool roof technologies include membranes, coatings, paintings, metal roofs, shingles, and tiles, as well as naturally cooling materials such as gravel or light-colored marble.

More recent developments in Passive Daytime Radiative Cooling (PDRC) technology have shown the potential of an advanced type of cool coatings, also named *super-cool materials*. PDRC technology is based on emitting long-wave thermal radiation toward space in the infrared spectrum between 8 and 13 µm wavelengths, i.e. the atmospheric window band that allows radiation pass to the outer space through the atmosphere without being absorbed. This enables the surface to consistently remain a few degrees cooler than surrounding air. Super-cool materials are engineered at the nanoscale to present an albedo much higher than 0.9 and an emissivity value close to unity in the atmospheric window.

Suitable surfaces		- Roads - Cycle paths - Public areas - Parking areas	- Façades: opaque and transparent surfaces - Roofs: all forms
Benefits			

References

Doulos, L., Santamouris, M. and Livada, I. (2004) 'Passive cooling of outdoor urban spaces. The role of materials', *Solar Energy*, 77(2), pp. 231–249. doi: 10.1016/j.solener.2004.04.005.

Lim, X. Z. (2020) 'The super-cool materials that send heat to space', *Nature*, 577(7788), pp. 18–20. doi: 10.1038/d41586-019-03911-8.

Manni, M. et al. (2022) '3 - Urban overheating mitigation through facades: the role of new and innovative cool coatings', in Gasparri, E. et al. (eds) *Woodhead Publishing Series in Civil and Structural Engineering*. Woodhead Publishing, pp. 61–87. doi: https://doi.org/10.1016/B978-0-12-822477-9.00013-9.

Pisello, A. L. (2017) 'State of the art on the development of cool coatings for buildings and cities', *Solar Energy*. Elsevier Ltd, 144, pp. 660–680. doi: 10.1016/j.solener.2017.01.068.

Santamouris, M. and Feng, J. (2018) 'Recent progress in daytime radiative cooling: Is it the air conditioner of the future?', *Buildings*, 8(12). doi: 10.3390/buildings8120168.

Santamouris, M., Synnefa, A. and Karlessi, T. (2011) 'Using advanced cool materials in the urban built environment to mitigate heat islands and improve thermal comfort conditions', *Solar Energy*. Elsevier Ltd, 85(12), pp. 3085–3102. doi: 10.1016/j.solener.2010.12.023.

4.7.2 Innovative materials with combined properties

THERMOCHROMIC MATERIALS

Thermochromic materials respond to the surrounding environmental conditions by reversibly changing their optical properties as a function of the temperature, moving from darker to lighter colors. On the building envelope, common cool materials can present possible disadvantages in winter, especially during extreme cold periods, when the reduction of solar gains may result in an increment of building heating loads. On the contrary, thermochromic materials limit the heat transfer through the envelope in summer, while increasing heat gain during cold conditions. Thermochromic pigments have also been incorporated to asphalt binder or cement paste to develop thermochromic pavements, resulting in a temperature reduction in summer and an increase during cold winters, in comparison to the respective common pavement materials.

Suitable surfaces

- Roads
- Cycle paths
- Public areas
- Parking areas
- Façades: opaque surfaces
- Roofs: all forms

Benefits

References

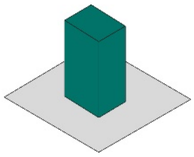
Hu, J. and Yu, X. B. (2019) ‘Adaptive thermochromic roof system: Assessment of performance under different climates’, *Energy and Buildings*. Elsevier B.V., 192, pp. 1–14. doi: 10.1016/j.enbuild.2019.02.040.

Qin, Y. (2015) ‘A review on the development of cool pavements to mitigate urban heat island effect’, *Renewable and Sustainable Energy Reviews*. Elsevier Ltd, 52, pp. 445–459. doi: 10.1016/j.rser.2015.07.177.

RETROREFLECTIVE MATERIALS

Retroreflective materials are able to reflect the incident light in the same direction of its source rather than diffusely within the urban fabric. In such a way, the entrapment of the solar radiation in the urban canyon caused by the application of common cool materials on vertical surfaces due to multiple reflections between façades and ground surfaces is avoided. Retroreflective materials have been tested for both coatings and tiles.

Suitable surfaces



- Façades: opaque surfaces
- Roofs: all forms

Benefits

References

Manni, M. et al. (2018) ‘An inverse approach to identify selective angular properties of retro-reflective materials for urban heat island mitigation’, *Solar Energy*, 176, pp. 194–210. doi: https://doi.org/10.1016/j.solener.2018.10.003.

Manni, M. et al. (2020) ‘Effects of retro-reflective and angular-selective retro-reflective materials on solar energy in urban canyons’, *Solar Energy*, 209, pp. 662–673. doi: https://doi.org/10.1016/j.solener.2020.08.085.

Mauri, L. *et al.* (2018) ‘Retroreflective materials for building’s façades: Experimental characterization and numerical simulations’, *Solar Energy*, 171(June), pp. 150–156. doi: 10.1016/j.solener.2018.06.073.

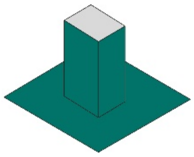
Morini, E. *et al.* (2018) ‘Optimized retro-reflective tiles for exterior building element’, *Sustainable Cities and Society*. Elsevier, 37(November 2017), pp. 146–153. doi: 10.1016/j.scs.2017.11.007.

Rossi, F. *et al.* (2015) ‘Retroreflective façades for urban heat island mitigation: Experimental investigation and energy evaluations’, *Applied Energy*. Elsevier Ltd, 145, pp. 8–20. doi: 10.1016/j.apenergy.2015.01.129.

COOL MATERIALS WITH PHOTOCATALYTIC PROPERTIES

Cool materials with photocatalytic properties combine high solar reflectivity and infrared emissivity with anti-polluting properties. Hence, the photochemical processes induced by the solar irradiation on photocatalytic surfaces promote the oxidation of various organic and inorganic pollutants.

Suitable surfaces



- Roads
- Cycle paths
- Parking areas
- Façades: opaque surfaces

Benefits

References

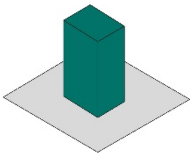
Chen, J. and Poon, C. sun (2009) ‘Photocatalytic construction and building materials: From fundamentals to applications’, *Building and Environment*. Elsevier Ltd, 44(9), pp. 1899–1906. doi: 10.1016/j.buildenv.2009.01.002.

Kyriakodis, G. E. and Santamouris, M. (2018) ‘Using reflective pavements to mitigate urban heat island in warm climates - Results from a large scale urban mitigation project’, *Urban Climate*. Elsevier B.V., 24, pp. 326–339. doi: 10.1016/j.uclim.2017.02.002.

COOL MEMBRANES WITH INTEGRATED PCM

Cool materials can also be integrated with phase change materials (PCM, i.e. materials able to store and release latent heat through chemical bonds) for associating the thermal benefits of high reflectivity with the latent heat storage capability of PCM as a passive technique for mitigating UHI and improving the building thermal energy efficiency. Such solutions have been mainly studied for their application on roofs showing effects both in terms of peak temperature reduction and improvement of energy efficiency due to the lower heat transfer through the envelope.

Suitable surfaces



- Façades: opaque surfaces
- Roofs: all forms

Benefits

References

Chung, M. H. and Park, J. C. (2016) 'Development of PCM cool roof system to control urban heat island considering temperate climatic conditions', *Energy and Buildings*. Elsevier B.V., 116, pp. 341–348. doi: 10.1016/j.enbuild.2015.12.056.

Lu, S. *et al.* (2016) 'Experimental research on a novel energy efficiency roof coupled with PCM and cool materials', *Energy and Buildings*. Elsevier B.V., 127, pp. 159–169. doi: 10.1016/j.enbuild.2016.05.080.

Pisello, A. L. *et al.* (2017) 'PCM for improving polyurethane-based cool roof membranes durability', *Solar Energy Materials and Solar Cells*. Elsevier, 160(July 2016), pp. 34–42. doi: 10.1016/j.solmat.2016.09.036.

Pisello, A. L. (2017) 'State of the art on the development of cool coatings for buildings and cities', *Solar Energy*. Elsevier Ltd, 144, pp. 660–680. doi: 10.1016/j.solener.2017.01.068.

Yang, Y. K. *et al.* (2017) 'Effect of PCM cool roof system on the reduction in urban heat island phenomenon', *Building and Environment*. Elsevier Ltd, 122, pp. 411–421. doi: 10.1016/j.buildenv.2017.06.015.

COOL PHOTOLUMINESCENT PAINTS

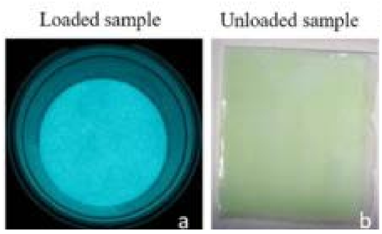
Cool photoluminescent paints combine the reflection of the incoming solar radiation, due to high solar reflectance with the emission of light for a certain interval of time after absorbing energy due to the phenomenon of fluorescence. Such solutions, which are still in the lab-development phase, might be used to reduce building energy consumption with respect to both cooling and electricity for lighting.

Suitable surfaces

- Roads
- Cycle paths
- Public areas
- Parking areas
- Roofs: flat

Benefits

Examples



Loaded (a) and unloaded (b) cool photoluminescent paint sample
Source: Rosso et al. (2019)

References

Levinson, R. *et al.* (2017) 'Methods and instrumentation to measure the effective solar reflectance of fluorescent cool surfaces', *Energy and Buildings*. Elsevier B.V., 152, pp. 752–765. doi: 10.1016/j.enbuild.2016.11.007.

Rosso, F. *et al.* (2019) 'Cool, photoluminescent paints towards energy consumption reductions in the built environment', *Journal of Physics: Conference Series*, 1343(1). doi: 10.1088/1742-6596/1343/1/012198.

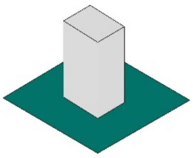
4.7.3 Evaporative pavements

EVAPORATIVE PAVEMENTS

Evaporative pavements are designed to be applied on ground surfaces for holding water for evaporative cooling purposes (i.e. the use of latent heat emissions due to evaporation to reduce surface temperatures) and for avoiding storm-water runoff. These solutions include:

- *permeable pavements*: constituted by concrete or clay bricks; the blocks themselves are impermeable, but are disposed so as to leave small apertures to allow water to pass around them;
- *pervious / porous pavements*: present a higher porosity than conventional impermeable pavements. The presence of holes and connected pores allows water to flow through the material and being stored when wet. The evaporation of water during the hot hours of the day contributes to reduce surface and air temperatures. Pervious pavers consist of high-porous concrete or asphalt, which allows water flow. They have a good performance for storm-water management purposes, but not for cooling, since they have higher thermal absorption and lower thermal inertia than conventional concrete pavements. Porous pavers generally present an interlocking structure, which can be filled with soil, gravel, or grass, the latter having the most significant cooling effect.
- *water-retentive pavements*: cement- or asphalt-based pavers developed to provide a consistent amount of water for evaporative cooling by avoiding its complete infiltration. The rainwater is kept in the layer close to their upper surface by water-retentive fillers.

Suitable surfaces



- Roads
- Cycle paths
- Sidewalks
- Public areas
- Parking areas

Benefits

Porous and permeable pavements
Pervious pavement

Water-retentive pavement

References

Bao, T. *et al.* (2019) 'A drainable water-retaining paver block for runoff reduction and evaporation cooling', *Journal of Cleaner Production*. Elsevier Ltd, 228, pp. 418–424. doi: 10.1016/j.jclepro.2019.04.142.

Qin, Y. (2015) 'A review on the development of cool pavements to mitigate urban heat island effect', *Renewable and Sustainable Energy Reviews*. Elsevier Ltd, 52, pp. 445–459. doi: 10.1016/j.rser.2015.07.177.

Qin, Y. *et al.* (2018) 'A new water-retaining paver block for reducing runoff and cooling pavement', *Journal of Cleaner Production*. Elsevier Ltd, 199, pp. 948–956. doi: 10.1016/j.jclepro.2018.07.250.

Santamouris, M. (2013) 'Using cool pavements as a mitigation strategy to fight urban heat island - A review of the actual developments', *Renewable and Sustainable Energy Reviews*. Elsevier, 26, pp. 224–240. doi: 10.1016/j.rser.2013.05.047.

Wang, J. et al. (2022) 'Evaporative cooling performance estimation of pervious pavement based on evaporation resistance', *Building and Environment*, 217, p. 109083. doi: https://doi.org/10.1016/j.buildenv.2022.109083.

4.8 Smart solutions

Smart solutions are mainly applied on the building surfaces; they encompass kinetic / responsive solutions, able to respond to external environmental stimuli, and animation and illumination technologies.

4.8.1 Kinetic / Responsive solutions

Responsive façades present surfaces able to manage internal conditions by dynamically modifying the characteristics of the building envelope in response to external environmental parameters. Among these, kinetic façades change over time, rather than being static, to respond to climatic factors, to reduce solar gain, to improve energy efficiency or for aesthetic purposes. Studies have shown that the modifications induced by responsive façades can improve the building energy performance by 40 to 65% compared to static ones (Mekhamar and Hussein, 2021).

The application of responsive façades can result in different environmental behaviours or goals and include several solutions. Responsive building envelopes feature real-time sensing, kinetic climate-adaptive components (e.g. for shading purposes), and adaptive materials (Hachem-Vermette, 2020). Adaptive building envelopes rely on building materials and components able to adapt to a range of climatic conditions (Addington, D. Michelle Schodek, 2004). Such materials have the capacity to alter passively their physical attributes, without the use of mechanical means or energy source (Velikov and Thun, 2013).

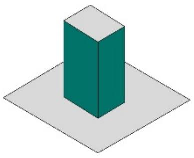
While adaptive building envelopes rely on the materials' intrinsic properties, intelligent building envelopes depend on the use of extrinsic control, computation and automation, allowing a larger range of responses aimed at optimizing the building's energy balance and indoor comfort under varying climate conditions (Hachem-Vermette, 2020). Such solutions include building automation, adaptive materials assemblies, automatic shading devices, and automatic ventilation dampers, amongst others (Addington, D. Michelle Schodek, 2004).

ELECTROCHROMIC AND PHOTOCHROMIC GLASS

Electrochromic glass is an energy-efficient glazing solution that can be controllably darkened in bright sunlight conditions and return clear during the evening or cloudy periods to optimize daylight levels and control solar heat gains and glare.

Photochromic glass can change its optical property in response to light intensity, reverting to its original state in the dark. The light transmittance of a photochromic window system drops significantly with increased solar radiation.

Suitable surfaces



- Façades: transparent surfaces

Benefits

References

Moschetti, R. *et al.* (2022) 'Assessing Responsive Building Envelope Designs Through Robustness-Based Multi-Criteria Decision Making in Zero-Emission Buildings', *Energies*, 15(4). doi: 10.3390/en15041314.

Hachem-Vermette, C. (2022), 'Solar Buildings and Neighborhoods: Design considerations for high energy performance', Springer.

Carmody, J., Selkowitz, S., Lee, E., Arasteh, D. and Willmert, T., (2004) 'Window System for High-Performance Buildings'. W. W. Norton & Company.

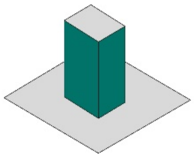
Granqvist, C.G. (1990) 'Chromogenic materials for transmittance control of large-area windows'. *Critical Reviews in Solid State and Material Sciences*, 16(5), pp.291-308. doi: 10.1080/10408439008242184

SOLAR RESPONSIVE FAÇADES

Solar kinetic responsive façades: respond to the variation of solar radiation levels to control heat, daylight or both. Several strategies can be implemented:

- *movement* of the whole building or some of its parts;
- *kinetic shading systems*: transformable systems that can have a wide range of movements to provide the most appropriate indoor day lighting levels and thermal conditions;
- *kinetic shading systems with PV cells*: integrated active solar energy systems to decrease the building energy consumption through the generation of electricity.

Suitable surfaces



Façades:

- opaque surfaces
- transparent surfaces
- louvres

Benefits

References

Hosseini, S. M. *et al.* (2019) 'A morphological approach for kinetic façade design process to improve visual and thermal comfort: Review', *Building and Environment*. Elsevier, 153(February), pp. 186–204. doi: 10.1016/j.buildenv.2019.02.040.

Mandaglio, M. (2019) 'Chameleon Building', *IOP Conference Series: Earth and Environmental Science*, 296(1). doi: 10.1088/1755-1315/296/1/012014.

Matin, N. H., Eydgahi, A. and Shyu, S. (2017) 'Comparative analysis of technologies used in responsive building facades', *ASEE Annual Conference and Exposition, Conference Proceedings*, 2017-June. doi: 10.18260/1-2--28052.

Mekhamar, A. A. and Hussein, A. H. (2021) 'Brief overview of climate responsive facades & its kinetic applications', *Engineering Research Journal*, 171(September).

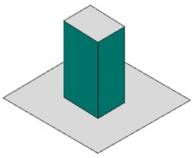
Sharaidin, K. (2014) 'Kinetic Facades: Towards design for Environmental Performance', p. 211. Available at: https://yazdanistudioresearch.wordpress.com/2011/02/10/kinetic-facade-products/.

WIND DRIVEN RESPONSIVE FAÇADES

Wind driven kinetic responsive façades respond to surrounding natural air current and wind conditions, aiming to provide high rates of indoor natural ventilation and to maintain high indoor air quality levels.

- *Air current responsive façades*: respond to surrounding air currents through the movement of façade elements to take advantages of local wind conditions for the natural ventilation of building indoor spaces.
- *Air current responsive façades with integrated wind turbines*: harness energy by converting wind and air current into mechanical or electrical energy in order to decrease the building reliance on non-renewable energy sources and increase energy efficiency.

Suitable surfaces



Façades:

- opaque surfaces
- transparent surfaces
- louvres

Benefits

References

Hosseini, S. M. *et al.* (2019) 'A morphological approach for kinetic façade design process to improve visual and thermal comfort: Review', *Building and Environment*. Elsevier, 153(February), pp. 186–204. doi: 10.1016/j.buildenv.2019.02.040.

Mandaglio, M. (2019) 'Chameleon Building', *IOP Conference Series: Earth and Environmental Science*, 296(1). doi: 10.1088/1755-1315/296/1/012014.

Matin, N. H., Eydgahi, A. and Shyu, S. (2017) 'Comparative analysis of technologies used in responsive building facades', *ASEE Annual Conference and Exposition, Conference Proceedings*, 2017-June. doi: 10.18260/1-2--28052.

Mekhamar, A. A. and Hussein, A. H. (2021) 'Brief overview of climate responsive facades & its kinetic applications', *Engineering Research Journal*, 171(September).

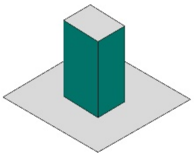
Sharaidin, K. (2014) 'Kinetic Facades: Towards design for Environmental Performance', p. 211. Available at: https://yazdanistudioresearch.wordpress.com/2011/02/10/kinetic-facade-products/.

4.8.2 Animation and illumination technologies

ANIMATION AND LIGHTING TECHNOLOGIES

Animation and illumination technologies for building surfaces respond to integrate aesthetic and functional requirements. These include:

- *mechanical media surfaces*: integrated screens and lighting elements, which change the perception of the building from motionless to changeable;
- *projections* interacting with the building surfaces;
- *computer animated light installations*;
- *led surfaces and interactive tiles*.

Suitable surfaces		- Façades: opaque surfaces
Benefits	-	
References	ARUP (2012) Groundbreaking concept integrating sustainable and digital tech. Available at: https://www.arup.com/projects/greenpix-zero-energy-media-wall.	

4.9 Traditional uses and materials

Traditional uses and materials include common solutions applicable on all urban surfaces.

TRADITIONAL USES AND MATERIALS

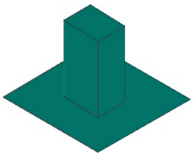
Traditional construction materials

- Asphalt
- Porphyry
- Stone
- Concrete
- Bricks
- Wood
- Glass
- Steel
- …

Traditional uses

- Windows
- Dormers
- Chimneys
- HVAC external units
- …

Suitable surfaces



- All

5 Conflicts and synergies among surface uses

The understanding of the main conflicts and the potential synergies among solar active and passive strategies and other solutions is an important step towards the definition of a comprehensive approach to urban surface use. Indeed, currently, the majority of the uses and solutions discussed in Chapter 4 are applied on urban surfaces independently from one another (Toboso-Chavero et al., 2018). This may cause inefficiencies and competition in the use of urban surfaces. The concept of integrating multiple urban surface uses to provide several benefits is yet to be extensively explored. To foster the definition of a comprehensive approach to urban surface use, the identification of main conflicts and the potential synergy among solutions is an important step.

In the framework of IEA SHC Task 63 - Subtask B, the solutions competing for the use of the same surfaces have been identified. Furthermore, recent scientific literature has been reviewed to collect integrated and innovative solutions currently under development. The investigation has been subdivided into two main sub-domains, i.e. ground and building surfaces respectively, since conflicts and synergies commonly arise when focusing on the same surfaces. Hence, some conflicts between solutions may be avoided when applied to different domains. As an example, cool materials and energy systems are generally conflicting, but the application of cool asphalt on ground surfaces is compatible with PV integrated at the building envelope scale. Moreover, the increased solar reflection due to the higher albedo of cool materials may be beneficial for the energy production of nearby active solar systems (Lobaccaro et al., 2017; Revesz et al., 2018).

5.1 Conflicts and synergies on ground surfaces

An outline of the solutions combining multiple solutions and of the conflicts arising on ground surfaces is presented in Figure 3.

	Green Solutions	Water Solutions	Urban Agriculture	Cool and Innovative Materials
Solar Energy Systems	✓ Landscape photovoltaic	✓ Floating photovoltaic Solar ponds	✓ PV greenhouses Aquavoltaics	? Increase of solar potential by reflected radiation

Figure 3. Conflicts and synergies among solar active and passive strategies and other solutions for ground surfaces.

On open areas, solar energy systems and green solutions are in conflict. Indeed, with regard to ecosystem and biodiversity loss, the development of urban solar energy infrastructure can result in significant land modification and habitats fragmentation (Gasparatos et al., 2017).

Water surfaces are generally not compatible with energy production, with the exception of solar ponds (Ranjan and Kaushik, 2014; Valderrama, Luis Cortina and Akbarzadeh, 2016). Water solutions, however, at urban ground level are often located in areas where the shadow cast by surrounding buildings and trees consistently reduces the amount of solar irradiation, making these surfaces less desirable for the installation of solar active systems. Therefore, in the majority of cases, no direct conflict arises. Furthermore, the opportunities for floating photovoltaic are being investigated and it may be possible in future to apply such systems also in urban water bodies of appropriate dimensions and with suitable solar irradiation (Sahu, Yadav and Sudhakar, 2016; Rosa-Clot, Tina and Nizetic, 2017; Cazzaniga *et al.*, 2018) .

Integration between energy systems and urban agriculture may be obtained through the application of semi-transparent PV modules on greenhouses roof (Cossu et al., 2016), and through “aquavoltaics”, i.e.

water deployed photovoltaic systems to be installed on aquaculture fields (Pringle, Handler and Pearce, 2017).

In the case of cool materials, studies have shown that their effects can be beneficial for PV systems applied on the building envelope in their proximity. Indeed, the energy production through solar applications can be further boosted by increased reflected solar irradiation. Studies conducted in Sharjah (UAE) have shown that the energy production from PV panels applied on the roof increases from +5 to 10 % in presence of cool coating roof paint (Altan *et al.*, 2019). Furthermore, measurements inside an urban canyon in Vienna (Austria) showed an increase of PV yield of around + 13 % by increasing the ground's albedo. Under the assumption of replacing the asphalt on the ground by highly reflective concrete with an albedo of 0.5, it was estimated that the PV yield would increase: by 20% on a wall point 3.5 m above ground, and by 7.3% on a wall point 12 m above ground (Revesz *et al.*, 2018).

5.2 Conflicts and synergies on building surfaces

Figure 4 presents an overview of the solutions integrating multiple urban surface uses and of the conflicts arising at a building envelope scale.

	Green Solutions	Water Solutions	Urban Agriculture	Cool and Innovative Materials
Solar Energy Systems	✓ Solar-green / Biosolar roofs Multifunctional façade system	✗	✓ Productive façades Solar greenhouses	? Increase of solar potential by reflected radiation

Figure 4. Conflicts and synergies among solar active and passive strategies and other solutions for building surfaces.

On the building envelope domain, active energy systems and green solutions are often designed and optimized to exploit their potential during summer periods, arising a competition between them for surface use (Penaranda Moren and Korjenic, 2017b). These two solutions, however, may work in synergy and benefit from one another. An example, described in the section below, are bio-solar or multifunctional solar-green roofs (Ciriminna et al., 2019).

With regard to façades, studies have focused on the creation of multifunctional systems integrating building greening and PV (Penaranda Moren and Korjenic, 2017a), and also investigate the possibilities of innovative technological solutions such as building-integrated microalgae photobioreactors (Cervera-Sardá, Gómez-Pioz and Ruiz-de-Elvira, 2014; Elrayies, 2018).

Research is also being conducted on the integration of renewable energy production and building-integrated agriculture BIA, besides the simple application of solar systems on greenhouses, through the novel concept of productive façades (Tablada et al., 2018). These solutions integrate PV panels and vertical farming, acting as modular systems to be substituted to common components of the building envelope (Kosorić et al., 2019).

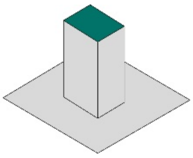
On roofs, the application of reflective materials is commonly in conflict with the presence of solar active systems. However, a recent study investigated the effect of cool roof applications on the performance of PV panels installed on the same surface, showing a likely improvement of 5 to 10 % of the electricity generation (Altan et al., 2019).

SOLAR GREEN / BIOSOLAR ROOFS

In solar green / biosolar roofs properly selected vegetation and photovoltaic modules are integrated to achieve both the enhancement of on-site renewable energy production and the promotion of biodiversity. Indeed, the combination of solar systems with green roofs in multifunctional solutions may provide potential habitats for certain species of plants and insects, and the shade imposed by panels may enhance plant diversity. Furthermore, the localized decrease of ambient temperatures caused by the green solutions, has been shown to reduce the operating temperature of PV cells, hence increasing the efficiency and useful lifetime of PV panels.

Compared with a conventional green roof, a solar roof includes an extra layer with the frames on which the PV panels are installed. The panels are usually tilted to optimize the incident solar radiation. However, some solutions also propose vertically mounted bifacial PV modules as a solution to combine photovoltaic power generation with green roofs at low reduced costs.

Suitable surfaces



- Roofs: flat

Benefits

Examples

GLS Bank Roof - Bochum (Germany) Source: Wikimedia (Molgreen - licensed under CC-BY-SA 3.0)

References

Baumann, T. *et al.* (2019) 'Photovoltaic systems with vertically mounted bifacial PV modules in combination with green roofs', *Solar Energy*. Elsevier, 190(July), pp. 139–146. doi: 10.1016/j.solener.2019.08.014.

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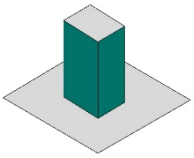
MULTIFUNCTIONAL FAÇADE SYSTEMS

Multifunctional façade systems integrate PV and greening to benefit from their synergies. The system typically comprises of PV modules installed on the outer layers, and a buffer layer to allow the growth of a green façade with climbing plants and the air circulation in the layer close to the building façade. The external photovoltaic layer protects the vegetation from high summer temperatures in summer and cold winter conditions, while also supporting the growth of climbing plants. At the same time, the vegetation provides a cooling effect for both the PV modules and the building façade.

Suitable surfaces



- Façades: opaque surfaces

Benefits

Examples

Multifunctional façade, Solar Decathlon 2021/2022 - Wuppertal (Germany) Photo: M. Wall

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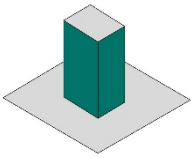
Penaranda Moren, M. S. and Korjenic, A. (2017a) 'Green buffer space influences on the temperature of photovoltaic modules: Multifunctional system: Building greening and photovoltaic', *Energy and Buildings*. Elsevier B.V., 146, pp. 364–382. doi: 10.1016/j.enbuild.2017.04.051.

Penaranda Moren, M. S. and Korjenic, A. (2017b) 'Hotter and colder – How Do Photovoltaics and Greening Impact Exterior Facade Temperatures: The synergies of a Multifunctional System', *Energy and Buildings*. Elsevier B.V., 147, pp. 123–141. doi: 10.1016/j.enbuild.2017.04.082.

BUILDING-INTEGRATED MICROALGAE PHOTOBIOREACTORS

In building-integrated photobioreactors (PBR), microalgae are cultivated into a controlled environment in closed systems installed on the façades, acting also as sun-shading devices. PBRs can act as solar-thermal cells. Furthermore, the biomass produced may then be processed and used as a bioenergy source for the building itself, as in the case of the BIQ building located in Hamburg, Germany.

Suitable surfaces



Façades:

- opaque surfaces
- transparent surfaces

Benefits

References

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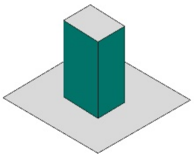
Talaei, M., Mahdavinejad, M. and Azari, R. (2020) 'Thermal and energy performance of algae bioreactive façades: A review', *Journal of Building Engineering*. Elsevier Ltd, 28(October 2019), p. 101011. doi: 10.1016/j.jobe.2019.101011.

PRODUCTIVE FAÇADES

Productive façades are being studied and tested to integrate both solar and farming systems on building façades. In such solutions, BIPV are used as shading devices and food production is achieved by building-integrated agriculture.

Productive façades allow the production of both food and electricity, while also acting as a passive device to reduce solar heat gain, and improving indoor thermal and visual comfort. Furthermore, they also contribute positively to the urban environment, enabling residents to grow food even in dense built-up environments while positively influencing the well-being of residents.

Suitable surfaces



- Façades: opaque surfaces

Benefits

Examples

Mockup of productive façade
Source: Tablada et al. 2018

References

Kosorić, V. *et al.* (2019) 'Survey on the social acceptance of the productive façade concept integrating photovoltaic and farming systems in high-rise public housing blocks in Singapore', *Renewable and Sustainable Energy Reviews*, 111(November 2018), pp. 197–214. doi: 10.1016/j.rser.2019.04.056.

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6 Conclusions

The work conducted within IEA SHC Task 63 leading to this report demonstrated the major role that urban surfaces play in the response to issues related to climate change and urbanization. Indeed, an increased utilization of all the surfaces of solar neighborhoods might offer several opportunities not only for producing renewable energy and correctly managing passive solar gains and daylight, but also for enhancing urban sustainability and climate resilience, and providing environmental, social, and economic benefits.

The main purpose of this report was to collect all the available solutions for the use of urban surfaces in solar neighborhoods, and to shed light on the major role that these might play in enhancing climate resiliency and sustainability. Based on an extensive literature review and on the discussion within IEA SHC Task 63, the suitable surface uses have been classified in eight major clusters (i.e. active solar energy systems, passive solar energy systems, green solutions, water solutions, urban agriculture, cool materials and innovative solutions, smart solutions, and traditional uses/materials). Furthermore, the most relevant solutions for each cluster have been analyzed, and the suitability of urban surfaces to integrate these solutions has been discussed, together with their contribution to the climate resilience and sustainability objectives. The results have been schematized in tables with the aim to provide an overview readily understandable from stakeholders involved in planning decisions, such as urban planners, designers, and municipalities.

6.1 Planning and designing surface uses in solar neighborhoods

Urban planning may play a key role in reducing conflicts and promoting the notion of urban surfaces as resources in the view of urban sustainability and climate resilience.

The information presented in this report aims at supporting the selection of urban surface uses in all phases of the design of solar neighborhoods. Criteria to be considered when choosing should include:

- the benefits provided by each solution or set of solutions and the contributions to site-specific objectives;
- the surfaces available in the area.

To further synthesize the contents of the report, an overview of the contribution of surface uses to objectives is presented in Table 1, and the relation between available urban surfaces and solutions is schematised in Table 2. These tables could support the preliminary identification of the solutions, while the specific tables in Chapter 4 could provide detailed information for the actual definition of solutions suitable for the urban area under study. The knowledge of the main conflicts and the potential synergies among solutions (Chapter 5) might also support the selection of innovative integrated solutions.

The discussions among Task experts emphasized the need for specific quantitative and qualitative approaches to address the design and implementation of surface uses in solar neighborhoods. To this aim, the next step of activities will be the development of a workflow incorporating sequential steps to address the multi-disciplinary challenges posed by the identification of surface uses and the evaluation of their contribution to climate resilience and sustainability.

Table 1. Overview of the objectives each surface use cluster contributes to. Primary contribution in blue, secondary in grey.

Climate resilience	Urban climate regulation	
	Water management	
	Air quality amelioration	
	Urban habitats and biodiversity preservation	
Sustainability	Energy self-reliance	
	Fresh-water availability	
	Food security	

: active solar energy systems; : passive solar energy systems; : green solutions; : water solutions; : urban agriculture; : cool materials & innovative solutions; : smart solutions.

Table 2. Overview of the urban surfaces' suitability for the application of each usage cluster. ✓: suitable
AS: active solar energy systems; PS: passive solar energy systems; GS: green solutions; WS: water solutions; UA: urban agriculture; C&I: cool materials & innovative solutions; SS: smart solutions; T: traditional uses/materials.

Surfaces			AS	PS	GS	WS	UA	C&I	SS	T
Ground	Road network	Roads	✓		✓	✓		✓		✓
		Cycle paths	✓		✓	✓		✓		✓
		Sidewalks	✓		✓	✓		✓		✓
	Open spaces	Public areas	✓		✓	✓		✓		✓
		Urban parks	✓		✓	✓	✓			✓
		Spaces in between b.	✓		✓	✓	✓	✓		✓
		Parking areas	✓		✓	✓		✓		✓
		Brownfields			✓	✓	✓			✓
	Topogr.	Rivers			✓	✓				✓
		Lakes	✓		✓	✓	✓			✓
		Hills			✓					✓
		Mountains			✓					✓
		Urban furniture	✓		✓					✓
Building	Façades	Opaque s.	✓	✓	✓	✓	✓	✓	✓	✓
		Transparent s.	✓	✓	✓	✓	✓		✓	✓
		Balconies	✓		✓		✓			✓
		Louvres	✓						✓	✓
	Roofs	Flat	✓	✓	✓	✓	✓	✓		✓
		Tilted	✓		✓			✓		✓
		Curved	✓		✓			✓		✓
		Other forms	✓		✓			✓		✓
	Intermed. spaces	Open atria		✓	✓	✓	✓	✓		✓
		Courtyards		✓	✓	✓	✓	✓		✓

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