Biosolar Roofs: A Symbiosis between Biodiverse Green Roofs and Renewable Energy

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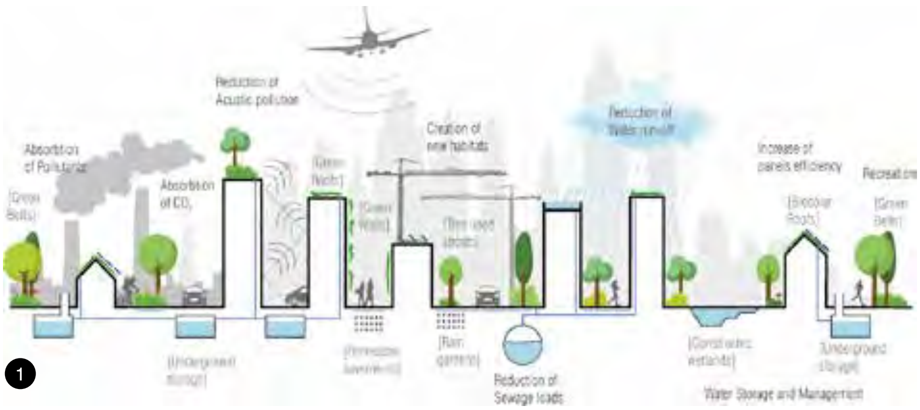


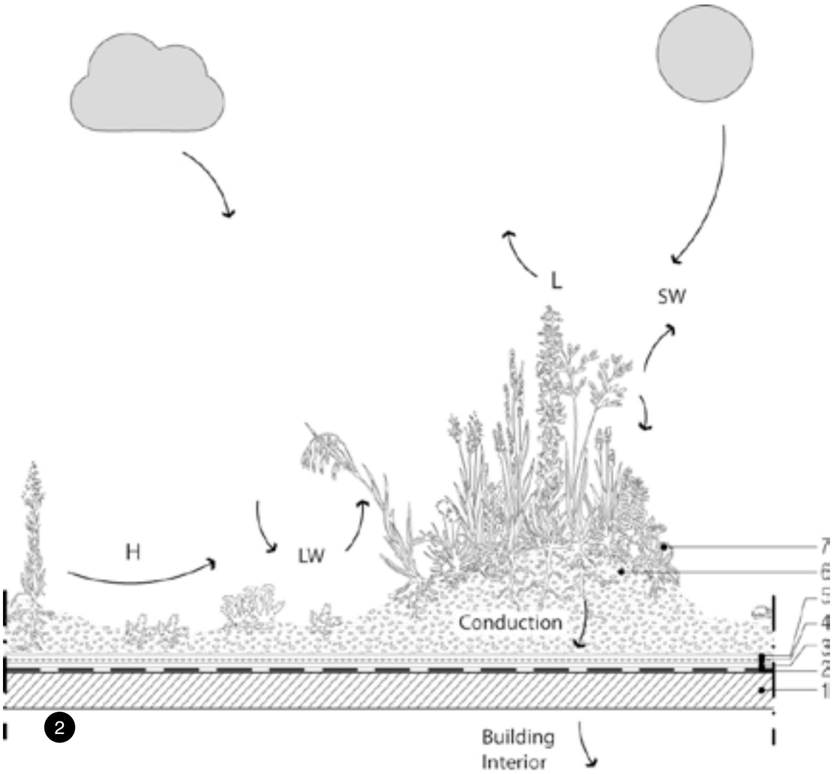
1. Ecosystem Services of Urban Green Infrastructure. The benefits in black text, the measures to achieve them in grey text between squared brackets.

The Role of Green Roofs in Cities - Reducing Urban Metabolism and Protecting Biodiversity

The human global population is predicted to reach 10 billion by 2050 and more than the 80% of the European population will live in cities.[1] With that, the energy consumption of the residential sector alone is expected to increase by about 48% in 2040.[2] At the same time, the current vertebrate extinction rate is 100 times higher than the natural one.[3] Both these socio-economic and ecological figures highlight the need to conserve the biological diversity and natural resources within the built environment. However, without a complete rethinking, the intrinsic nature of our cities is not conceived to fulfil this aim. This rethinking involves reviewing the drivers of city planning and structure, to consider the needs of a continuously growing and demanding population.

Cities have to be considered as biophysical systems, a perspective aiming to fill the gap between social-economic and ecological approaches, yet driven by the concept of urban metabolism. In this sense, cities behave as heterotrophic ecosystems[4] in a framework of input-output analysis by depleting energy (often not renewable) from outside sources to sustain its inhabitants' survival and activities (e.g. fuel, food and materials) while producing waste and heat in the environment as a by-product. The process of city development and transformation has resulted in the alteration of natural biogeochemical cycles (e.g. water and carbon), local climates (e.g. urban heat island effect), changes in land use and cover, loss and fragmentation of natural habitats and their ecosystem functions and services. Hence, adopting an ecosystem perspective to study cities as one ecosystem rather than an analogue of several ecosystems is necessary. This implies that city-environment relationships are grasped in a circular rather than linear perspective, and other important considerations include trade-offs between economic, social and environmental concerns and services, as well as urban abiotic (e.g. water, air, soil) and biotic (e.g. animals, plants and humans) interactions.[5]

Thanks to advances in interdisciplinary studies, the concepts of urban metabolism and ecosystem can be applied at different scales in sustainable design and planning.[6] For example, an urban green infrastructure is a multifunctional tool fulfilling several functions. Green and blue spaces can be used for recreation, local climate mitigation (reduction of the Urban Heat Island effect), CO_2 absorption, air and water purification, and partial restoration of biogeochemical cycles (Figure 1).[7] The ecological importance of urban green infrastructure will increase if it were linked to the greater ecological network that considers the interaction between urban green spaces and natural, semi-natural and rural areas. However, conflicts arise when considering the lack of space in dense urban agglomerations, where it seems less remunerative to invest into the implementation and maintenance of green open spaces, compared to investments in new settlements and grey infrastructure.



2. Energetic balance of a green roof. L= Latent heat flux; SW = Shortwave Radiation; LW = Longwave radiation; H =Sensible heat flux. The section represents a biodiverse green roof with different substrate thickness, several vegetation forms and heterogeneous cover. The stratigraphy: 1) bearing structure and draining slope, 2) waterproof membrane, 3) root barrier and mechanical protection, 4) drainage, 5) filter, 6) substrate and 7) vegetation

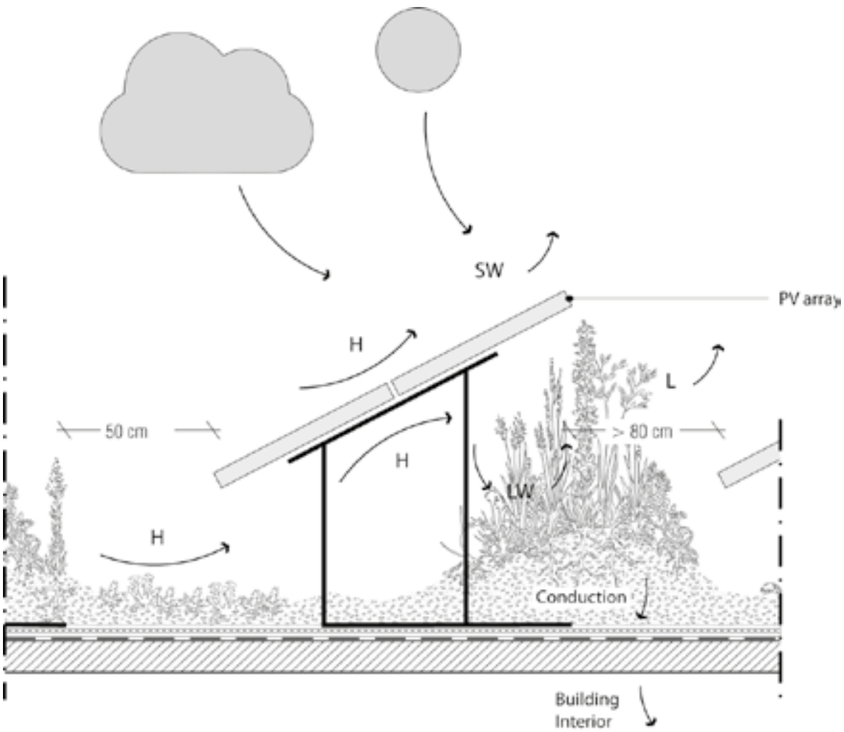
Green roofs, one of the main pillars of sustainable architecture and the urban green infrastructure, can answer the demand of protecting and connecting/ habitats in dense cities.[8] Another application of the reduced metabolism approach is the gradual replacement of fossil fuel in favour of renewable energy. At the building scale, it is possible to refer to photovoltaic panels and micro-wind turbine for electricity production, and solar thermal for warm water production. In terms of metabolic balance, cities can, in fact, produce energy while providing habitats to re-establish natural cycles and lost ecosystem services. However, although the cooling effect of vegetation and substrate on optimising panel performance is proven,[9] the integration of the two systems on the rooftops is yet to be systematically adopted. In fact, one of the key aspects of green roofs is its multi-functionality, which is the capacity to fulfil several benefits on the same area and often at the same time.[10] These include the improvement of the energetic and the acoustic behaviour of buildings;[11] reduction and amelioration of storm water runoff;[12] pollution abatement and carbon sequestration;[13] regulation of the local microclimate and reduction of the urban heat island effect[14] especially when combined with vegetation at the ground level;[15] provision of recreational space;[16] provision of habitats for wild flora and fauna[17] and implementation of the urban ecological network.[18] There are also other indirect economic benefits such as the protection of the waterproof membrane beneath the substrate thus expanding its life span, and the increase of the property value.[19]

Integrating Solar PV Panels on Green Roofs

The positive effect of vegetation includes increasing the efficiency of solar and photovoltaic panels due to its cooling effect and reduced particulate matter accumulation.[20] A similar amelioration could be obtained in high reflective roofs (white or cool roof) with albedo values in the range of 0.7-0.85 at factory. However, the albedo on installed roofs will reduce with time because of the deposition of dust and the formation of fungi and algae.[21] Hence, the membrane has a reduced lifespan and higher energy consumption in a life cycle than if a green roof protected it.[22] Furthermore, the adoption efforts of cool roofs as a global strategic means to mitigate global warming are considered negligible.[23]

The integration of green roofs and solar PV panels i.e. Green Roofs Integrated Photovoltaic Systems, instead, is a win-win solution where the benefits of greened surfaces are brought into otherwise sterile and unused roof tops while obtaining a yield in PV efficiency.[24] On the other hand, the shade of the panels reduces the evaporation rates and drought stress, thereby contributing to plant species richness and arthropod diversity.[25]

The cooling effect of green roofs is not primarily due to their albedo but the loss of latent heat via evapotranspiration.[26] Therefore plant selection is crucial, with the most influential aspects relating to the Leaf Area Index (LAI) of the vegetation. LAI is the leaf area per unit of ground area covered by the projected area of the crown and it affects: 1) the way the vegetation reflects the incident solar radiation as well as, 2) the capacity to contrast wind speed and turbulence. Higher LAI keeps the air more humid.[27] For the same reason the substrate depth, moisture and density play an important role. In the energy balance of a green roof[28] the short wave solar radiation (SW) is partitioned between sensible heat flux (H) due to convection from growing medium (H_g) and foliage (H_f), the latent heat flux (L) due to evapotranspiration from growing medium (L_g) and foliage (L_f), the conduction of heat into the growing medium (and then to the roof structure) and the longwave (LW) radiation to and from the growing medium and foliage (Figure 2). Convection



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3. Energetic balance of a green roof and solar VP. L= Latent heat flux; SW = Shortwave Radiation; LW = Longwave radiation; H =Sensible heat flux. Biodiversity is enhanced by the different substrate thickness while favouring low growing plants in front of the panels (for a stripe up to 50 cm wide) and higher biomass at the back and under the panels. The distance between arrays should be kept at about 80 cm to create more habitat patches.

is influenced by the difference in temperature between the air and the surface of the leaves, wind speed and LAI. L_f (plant transpiration) is determined by the stomata resistance which in turn depends on the light intensity, soil moisture and pressure difference between the leaf and the air. The soil, H_g (convection) and L_g (evaporation) are sensitive to the wind speed within the foliage, but the first depends on the temperature difference between the soil surface and the air, the second on mixing ratio of the growing medium and the air. With that, a 40% increase in the specific heat capacity of saturated soil will double its thermal conductivity and reduce its albedo values when compared to bitumen and gravel roofs, comparable to the brightest white roof.[29]

In the energy balance of green roofs and solar PV panels, other convective, radiative and conductive processes take place (Figure 3): the radiation and convection from the PV to the foliage, and the microclimate below and above the panel; the absorption of the incoming solar radiation to power production as well as conduction to the above and below part of the panel; the absorption of the incoming solar radiation to power production and conduction to the above and below part of the panel.[30] In fact, the combination PV and green roof can lead to a reduction of up to 50% of sensible flux than with black roof.[31] However, the cooling benefit of the green roof decreases if the position of the panels is over 20 cm due to higher wind exposure that speeds the evaporative process thus reducing the convective cooling effect due to the foliage.[31]

Biodiverse Green Roofs

Biodiverse green roofs were developed as a new typology in Switzerland in the last 10 years after the work of Stephan Brenneisen, as a provision of new habitats in urban cores.[33] The key design features that differentiate it from other green roof typologies, namely extensive, simple-intensive and intensive, can be synthesised in:[34]

1. Spatial heterogeneity.

a. Variable substrate thickness (Figure 3). In temperate climates, 8-10 cm of substrate can host Crassulaceae species (e.g. Sedum sp.), mosses and few kinds of grass. Depths greater than 10 cm can also host forbs. In particular, in 12 cm of substrate forbs and grasses out compete for the Crassulaceae species allowing the establishment of a balanced mixture of forbs and grasses meadow. In thickness greater than 15 cm, grasses predominate. Shallow substrates and low vegetation cover favour predatory insects of xeric habitats.

b. Different kind of substrate (Figure 4). Generally, the substrate used for extensive green roofs is constituted by a commercial mixture of light aggregates in different granulometry (recycled materials like crushed- bricks and ceramics, volcanic materials like lava beams, pumice and zeolite, expanded aggregate like clay and slate) and organic material (peat, sterile compost, etc.). To sustain a bigger floristic diversity and host specific animal species, it is possible to use another coarse aggregate like silica sand, clay, silt, slate, pebbles and top soil (paying attention to avoid contaminated soils or containing exotic invasive species in the seed bank). Areas with solely sandy gravel favour thermophilous insects.

Figure 4. Use of different substrate kinds. The green roof of the Stücki Shopping Centre in Basel. The concept of the design was to mimic a river bank with different substrate composition and vegetation kinds. Image by Chiara Catalano

Figure 5. Use of branches as extra structural features. The green roof of the Old Messe in Basel; the plastic cap and tube are used as pitfall traps for the biodiversity monitoring of the insect living/visiting the roof. Image by Chiara Catalano

Figure 6. Use of pebbles and gravel as extra structural features. The green roof of the Jacob Burckhardt Haus in Basel. Image by Stephan Brenneisen

c. Extra design features (Figure 5 and 6). Stones, trunks, branches constitute a shelter against weathering for micro fauna as they affect micro-climatic conditions. Temporary ponds offer water source for insects and birds and favour the establishment of ephemeral biocenosis of wet areas. Moreover, ground nesting birds rely on green roofs to nest due to the scarcity of proper habitats on the ground because of land use change in favour of agricultural fields.

2. Use of native plant species.

The inclusion of native species improves resilience in the artificial ecosystem as they are already adapted to the local conditions. In this way, green roofs can be part of the greater ecologic network as they host metapopulations of targeted species that otherwise would not survive in urban environments. Moreover, nurseries would be encouraged to produce seeds and plants of native species.

3. Low maintenance and disturbance.

It is known from applied ecology that moderate disturbance corresponds with higher biodiversity. For this reason, biodiverse green roofs do not need maintenance such as grass cutting or the eradication of unwanted *phanerophytes* (shrubs and trees). However, the low maintenance regime required of the biotic and abiotic parts of the system, should not eliminate the periodical check-up of the technical and structural aspects.

Project "Biosolar Roofs" - Promoting the Symbiosis of Renewable Energy Production and Biodiversity

The Green Roof Competence Centre (now Urban Ecology Research Group) of the Zurich University of Applied Science (ZHAW, Switzerland), together with other partners from Austria (BOKU), UK (Onsite Training), Sweden (SGRI), France (INIT), Spain (Link) and Hungary (Sound Garden) cooperated between 2011-2015 to develop a common strategy to promote the combination of solar energy and biodiverse green roofs among professionals. This project named Biosolarroofs (www.biosolarroof.com) was funded by the EU-Life Long Learning Program (Leonardo Transfer of Innovation) with a total funding support of 250,000€.

The project aimed to overcome the conflict between the emerging European solar panels (PV and thermal panels) and the older green roof markets, both targeting rooftops. Biosolar roofs are the combination of biologically diverse greened roofs and photovoltaic and thermal panels which generate renewable energy from the sun. The win-win situation characterising this combination was one of the drivers that had the Biosolar roof project successfully funded by the Life Long Learning Program of the European Community (Leonardo Transfer of Innovation).

The primary aim of the biosolarroof project was to develop accredited training programs that would nurture workforce skills to install and maintain a biodiverse green roof that will hold solar panels as well as stimulate pollinators. The first step was to set up a preliminary investigation on the benefits related to the combination of biodiverse green roofs and solar PV. The second step was to inform professionals and decision makers. This was followed by developing training facilities to implement and maintain the biosolar roofs with a quality/standard level.

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Key Design Features of Biosolar Roofs

1) Spatial heterogeneity

Biosolar green roofs, as well as biodiverse green roofs, provide spatial heterogeneity through its varying substrate thickness (Figure 3). In front of the panels, where the conditions favour low growing species and succulents, the recommended thickness is 5-7 cm for a length of 50cm. At the back of the panels, where the conditions favour plant growth and biomass, the recommended thickness is 15 cm. Where the solar panels are not present, it is convenient to enlarge the distance between the solar arrays up to 80 cm and increase the substrate thickness up to 20 cm. It is also advisable to increase the area free from vegetation at the edge and at the water outlets to favour xeric insects. As the substrate constitutes a ballast for the solar panel structure against the wind, the use of excavation soil mixed with sandy-gravel from local pits is recommended.

2) Plant species selection

The variation of the substrate thickness and the shade of the panels support plant species with different adaptabilities. Drought and stress tolerant species can be planted at the front of the panels while at the back where conditions are shaded and humid, competitive and ruderal species are recommended. Plant species have to be of the local biogeographic region with a species richness of 6-10 species per square meters. What is important is that the plants do not shade the panels thus affecting the energy production; therefore, pulvinate, creeping and prostrate plants should be preferred (Figure 7 and 8).

3) Extra designing features

Similar to biodiverse green roofs, temporary ponds, pebbles and branches can help inhabitants of the roof overcome dry periods. It is also important that the water necessary for plant growth can reach the area below the panels. This can be achieved by applying a material layer that will distribute the water homogeneously through capillary action (e.g. fleece).

4) Maintenance

Maintenance of biosolar green consists the eradication of phanerophytes and invasive weeds, as well as cutting of tall plants growing in front and between the panels thus shading them. Mowing is not generally required, and maintenance is minimal, at a frequency of about once a year. If mowing is carried out, it is important that the biomass is removed to avoid an excessive nutrient content accumulation that would compromise the established habitat. In fact, in nature, wild species grow in poor nutrient soils.

Lessons Learned and Best Practice from the Biosolar Roof Project

Six European countries constituted the partnership of the project, each struggling with the implementation of renewable energy and biodiversity conservation. However, biodiverse green roofs as measures within the Green Infrastructure toolbox are not yet homogeneously fostered. The main objectives were the levelling of the differences in weighting and targeting measures in each country and its own political/professional systems, as well as a shift towards an improvement of biodiversity conservation measures. Each country with its own existing legal and political basis will obtain a customisation of the courses.

Preliminary research findings

A study monitoring the biodiversity of a biosolar roof installed in London at the Queen Elizabeth Olympic Park confirmed the positive effect of the integration of biodiverse green roofs and solar PV. On the roofs of 2500m^2 in area, built to mimic the open habitat of the Thames corridor, 92 plant species were found while the assemblage variation was identified in the proximity of solar panels. With that, 50% of the arthropods found on the roof are considered of conservation importance while the presence of rare and common birds on the roof attested good foraging source. Moreover, species structural diversity was higher in the proximity of solar PV and piled elements (woods and rubbles) especially over the dry season, thus proving that solar panels enhance the spatial heterogeneity of biodiverse green roofs.

Future research and implementation

Even if green roofs positively affect energy production, the systematic use of combined technologies is still scarce. This is partly due to the lack of research on optimal plant selection that will increase beneficial symbiosis. In fact, an effective gain in energy production produces varying results worldwide, as correct positioning and orientation of panels is crucial. This increases the level of uncertainty and favours the use of white roofs that are less expensive and easier to apply and maintain. In the example of a recent innovation in Switzerland, it adopts vertical bifacial panels east-west oriented on green roofs with hairy plants and white substrate in order to increase the albedo of the green system.[37] Finally, more research is needed on the PV-plant-substrate relationship and on the refugia effect played by the used extra structural features (e.g. PV panels, pebbles, trunks and branches) in order to implement the ecological role of Green Roofs Integrated Photovoltaic systems: biosolar roofs. CG

Figure 7. Biosolar roof. Green roof of the Palais Beaulieu in Lausanne. The dominant specie is Anthyllis vulneraria a yellow flowering hemicryptophyte (plants with perennial buds close to the grounds) typical of European semi-dry grasslands (Mesobromion). Image by Antoine Lavorel

Figure 8. Biosolar roof. Green roof of the "Werkhof Scheidegg" in Winterthur. The dominant species are Sedum acre and Petrorhagia saxifraga; the first typical of basophilic grasslands (Alysso-Sedion), the second of calcicolous steppe grasslands (Stypo-Poion). In foreground Campanula glomerata typical of semi-dry grasslands (Mesobromion). Image by Chiara Catalano

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