ICE MANUAL OF BLUE GREEN INFRASTRUCTURE

Green roof chapter

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1. Introduction

Green roofs are an engineered roof system that typically includes a growing medium and vegetation element installed over a waterproofing and drainage layer. Green roofs offer a sustainable construction technology that can deliver a range of **environmental** benefits such as: habitat for biodiversity, SuDS (retention, detention, water quality), reducing the Urban Heat Island (UHI) effect, improving air quality, and improving building energy/noise performance (Oberndorfer et al, 2007) Some green roofs can also deliver **social** benefits, for instance by providing recreational space and/or opportunities for food growing (Bianchini and Hewage, 2012; Shafique, Kim and Rafiq, 2018). There can be **financial** benefits too, as green roofs can extend the life of roof coverings and reducing building energy consumption costs (Shafique, Kim and Rafiq, 2018). In urban areas, roof space can constitute a major land use/cover area. As such, green roofs represent a significant potential for renaturing urban areas (Bianchini and Hewage, 2012; The Ecology Consultancy, 2014).

There can be various drivers for including a green roof system into a project beyond the broader gains outline above. For instance, to achieve a high-quality rating for a built environment sustainability accreditation scheme such as BREEAM (Building Research Establishment Environmental Assessment Method), to meet a planning condition or requirement, to contribute to biodiversity net-gain, and to comply with local and national strategic plans and policies, such as the London Plan (Greater London Authority, 2021) green roof policy and its accompanying technical report, Living Roofs and Walls – from policy to practice (Grant and Gedge, 2019).

A series of benchmark publications are available in relation to green roof design guidance, and these will be signposted throughout the chapter:

- the Green Roof Organisation's (GRO) green roof code of best practice (GRO, 2014) and 2021 Anniversary edition (GRO, 2021);
- the German organisation Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V. (FLL) green roof guidelines for planning construction and maintenance of green roofs (FLL, 2018);
- the British Standards Institute (BSI) specification for performance parameters and test methods for green roof substrates report (BSI, 2019);
- Buglife – The Invertebrate Conservation Trust's creating green roofs for invertebrates best practice guidance (Gedge *et al.*, 2012);
- The London Living Roofs and Walls report (Grant and Gedge, 2019).

These documents should be viewed as key resources for the planning, delivery and maintenance/stewardship of green roof systems. The following chapter is intended to provide a synthesis of these guidance documents, in the form of an introductory 'how to' guidance for the different types of green roofs that can be implemented. It does this by presenting an introduction to the different types and components of green roofs. It then provides a practitioner's approach to the decision-making process involved in the implementation of different green roof systems in relation to typical motivations for installing green roofs, and potential constraints that may determine the type/design of the system that can be installed. Finally, there is an overview planning policies and sustainability certification systems that can be drivers for green roof implementation.

2. Different roof types/key features

A variety of different green roof typologies exists. Typologies are typically related to designed for function, as well as constraints in relation to the location that they are installed, and local characteristics in terms of green roof industrial practices. The typologies are typically created through manipulation of various construction components (layers) to influence the visual appearance and/or performance in terms of the ecosystem services (benefits provided by natural systems) that the green roof provides. Whilst the materials within these layers can vary considerably, most modern green roof systems follow a relatively standard build-up system consisting of a series of layers. This includes: 1) vegetation, 2) substrate, 3) filter layer, 4) drainage layer, 5) protection mat and 6) waterproofing. An illustration of these layers is presented in Figure 1.

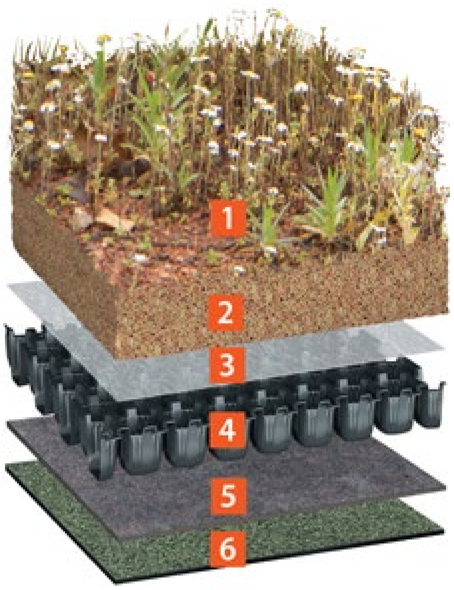

Figure 1. Typical extensive green roof build-up*. (1) vegetation layer; (2) substate layer; (3) filter fleece; (4) drainage layer; (5) protection mat; (6) waterproofing layer. © Bauder*

General green roof typologies

Green roofs typologies are generally categorised in relation to characteristics such as substrate depth/weight, vegetation type, and maintenance requirements, although there can be some overlap between typologies. The two main categories are 'intensive' and 'extensive'. Intensive roofs have deeper substrates (>150 mm), can support all sizes and types of plants and usually require regular maintenance and inputs such as irrigation. Extensive green roofs have a shallower substrate layer (typically <150 mm), typically support low-growing, drought-tolerant plants, require little maintenance or inputs and are lighter weight and less expensive. Table 1 below summarises the key characteristics associated with the main and widespread green roof typologies.

Table 1. Summary of main green roof categories and typologies and their key characteristics

Main category	Extensive			Intensive
Type	**Sedum blanket**	**Sedum/wildflower on substrate**	**Biodiverse**	**Recreational Space/ Urban Agriculture**
Vegetation	Sedum only	Sedum or native wildflowers	Bespoke native wildflowers/grasses	Lawn, perennials, shrub, trees (crops)
Substrate depth	-	80-100 mm	Undulating (average 130 mm)	>150 mm
Weight	44 kg/m²	60-100 kg/m²	~150 kg/m²	>180 kg/m²
Maintenance	Low	Low	Low	High

Green roof guidance such as the GRO code (GRO, 2014, 2021) and FLL guidelines (FLL, 2018) provide greater detail on factors related to the above typologies, and also include a third main category – semi-intensive – which as the name suggests is an intermediate type of green roof, with a substrate depth between 100-200 mm that allows for a more varied vegetation, including shrubs and woody plants that are not generally planted on extensive roofs. As green roof designs and technologies advance, additional categories of green roof are becoming more mainstream, for instance 'biosolar' roofs that combine a green roof with photovoltaic (PV) solar panels, and 'blue-green' roofs that are specifically designed for stormwater attenuation, holding and attenuating much larger volumes of stormwater than standard green roofs.

3. Key factors to consider at outset of green roof project technical design

When planning a green roof, there are a number of factors to consider in relation to developing, delivering, and maintaining a successful green infrastructure system capable of sustaining the targeted benefits. These include:

- Whether the green roof is part of a **retrofit project** – in which case many of the limitations of the green roof design will be predetermined; or **new build** – where there is opportunity to specifically design the supporting building/structure to enable greater flexibility in terms of the green roof design.
- Understanding the **loading constraints** (e.g. <100kg/m2; 150-250kg/m2; >250kg/m2). This is one of the key aspects influencing the type of green roof system that can be installed and the scale of benefits and co-benefits that can be achieved. For retrofit green roofs, this is determined by the existing structure. For new build there maybe opportunity to adapt the loading capacity so that the desired type of green roof, and green roof benefits, can be achieved. For this reason, it is recommended that the required function and performance of the green roof are determined at the structural design stage.
- The **target/motivation** for installation of a green roof. There can be many reasons for installing a green roof. For example, is it to create a new recreational space? A grow-your-own opportunity? To enhance/mitigate biodiversity? To provide a Sustainable Drainage Systems (SuDS) function? To reduce the carbon emissions/energy demand associated with a building or development? To meet the requirements for BREEAM, excellence? To meet planning conditions/consent? To mask a building? Or just to provide a pleasant view for buildings overlooking the roof? If designed appropriately, a green roof can simultaneously deliver, one, some, or all of these intended benefits.
- **Stewardship** is of critical importance, and a long-term management and maintenance plan should be specified at the outset of a project, as without this, the intended benefits of the

green roof may not be sustained (Connop and Nash, 2020; GRO, 2021). Central to stewardship planning is both developing a suitable management/maintenance process, and also ensuring that sufficient resources are available to sustain the process long-term. To complement this, it is also useful to have either a formal or informal evaluation plan for assessing the green roof performance (Dumitru and Lourido, 2021; Dumitru and Wendling, 2021). Impact assessment and performance evaluation enables the management and design of the green roof system to be adaptable to changing conditions, pressures and needs. Stewardship plans can come in a variety of formats (from installer maintenance agreements to volunteer groups) and the intensity of maintenance is typically dependent upon the type of green roof installed (GRO, 2021).

4. Technical installation motivations and requirements

The following sections provide a summary of key technical considerations and requirements for a green roof based on the main motivating factors that typically act as drivers for green roof installation. Technical guidance is provided for the main components of the green roof that vary according to motivation/typology (e.g. vegetation, substrate, drainage and waterproofing), specific to each green roof 'type': biodiverse, Sustainable Drainage Systems (SuDS), recreational space/urban agriculture, biosolar, and carbon/energy efficiency. This is followed by a brief overview of some specialist green roof types/motivations that are relatively uncommon and/or cross over with other green infrastructure approaches, and examples of key planning policies and sustainability certification systems that motivate green roof installation.

Biodiversity

Biodiverse green roofs are designed as habitat to benefit wildlife such as insects and birds. Numerous studies have demonstrated the value that green roofs can have supporting biodiversity in urban areas if designed appropriately (Baumann, 2006; Kadas, 2006; Pearce and Walters, 2012; Madre *et al.*, 2013; Kyrö *et al.*, 2018). This value can be enhanced, when green roofs are designed to support locally typical and important biodiversity (Nash *et al.*, 2019).

Biodiverse green roofs can be created as an analogue for a specific habitat, for instance a local Biodiversity Action Plan (BAP) habitat, and this may be a specified planning condition for a project. Early prototypes of the biodiverse roof were called 'brown' roofs, because they were designed based on brownfield ecology principles: reusing aggregates from site and allowing them to vegetate and colonise naturally. However, due to a combination of poor substrate quality, and slow colonisation, the term 'brown' roof was dropped in favour of 'biodiverse' roofs, which have a seeded and/or plug-planted vegetation layer (GRO, 2021). Whilst biodiverse roofs can be visually attractive, aesthetics are not the main driver and it should be understood that ecological habitats can look 'untidy' at certain times of year, but that this is a crucial part of the natural lifecycle of these roofs, and key to their function in supporting biodiversity.

Building constraints: Buildings will need a loading capacity >100kg/m^2 to allow for sufficient substrate depth to create a biodiverse green roof. Biodiverse roofs will require deeper substrates than some other roof systems (e.g. sedum systems) and as the system weight is due mainly to the depth of substrate. Deeper substrate will enable a greater variety of plants to be able to persist on the roof, and provides an opportunity for creation of a greater variety of habitat niches. It is important to note that greater depths of build-up can also cause issues with height constraints, if these are a limiting factor for the location of the green roof installation.

Drainage: For biodiverse roofs the drainage layer needs to enable water to drain freely from the substrate, but some water retention via the drainage layer (and substrate) is important. Ideally a drainage board with good water holding capacity should be used to help support the less drought tolerant planting. Creating variation in the hydrology of the roof can enhance its ecological value by increasing habitat diversity. Opportunities for creating ephemeral wetlands, dew ponds or wetland roofs can add value for biodiversity (Nash, 2017; GRO, 2021).

Substrate: Biodiverse roof substrates typically need to be lightweight, free-draining, non-compacting and low-nutrient, with a neutral pH. Using locally-typical substrates, and/or locally sourced substrates, can add to the biodiversity and sustainability value of a project. Nonetheless, substrates should comply with the GRO code (GRO, 2014, 2021) and FLL guidelines (FLL, 2018), and should therefore typically be sought from suppliers that comply to these standards. Biodiverse extensive roof substrates generally have a low organic content to promote greater floristic diversity.

Using site-based material can facilitate sustainable practice and the potential reuse of local typical substrate. However, whilst this approach enables the existing seed bank to be transferred to the green roof being installed, this method carries some risk and as such, there are various aspects that need to be considered. For instance, the substrate would need to be screened and analysed to confirm its suitability and must be carefully harvested and stored. Stock piling of substrate can cause problems with anaerobic composting and contamination (infestation with weed seed, etc). Using small amounts of the site topsoil as a “top dressing” offers an alternative approach for the site’s seed bank to be transplanted to the roof, without risking the viability of the green roof. A further important consideration is to ensure the roof does not pose a fire risk. Standard guidance is that the substrate must contain less than 20% organic content to comply with the GRO code (GRO, 2021) and GRO fire risk guidance document (GRO, 2018).

Varying the type of substrate installed and varying the depth by creating ‘microtopography’ can encourage diversity in vegetation and provide microhabitats that benefit plants and insects. Avoiding peat-based substrates and plugs is good practice. As well as promoting sustainability by reducing the carbon cost, it helps to avoid trade-offs such as the negative biodiversity impacts from peatland degradation.

Vegetation: The selection of plants to support biodiversity will depend on each regional context (Köhler & Ksiazek-Mikenas, 2018). The vegetation composition may be specified if there is, for instance, a planning requirement to provide a local BAP habitat (**Figure 2**) or a target habitat identified during an Ecological Impact Assessment. Biodiverse roof vegetation generally comprises native wildflowers that are relatively drought-tolerant, and best practice is to take inspiration from local priority habitats/species and planting lists and to use native species of local provenance (example links, Floral Locale guidance). Vegetation structural diversity (e.g. tall, short, dense/tussock, sparse vegetation and areas of bare ground) is also important as this provides a broader range of niches for a broader range of species (Gedge *et al.*, 2012; Madre *et al.*, 2013; Nash *et al.*, 2019). A mixture of seeds and plug plants may be used to establish vegetation and planting a variety of species will offer a broad range of resources that will benefit a wide range of biodiversity. To benefit pollinators, plant species should be selected to ensure that flower forage is provided throughout the entire key season (early spring to early autumn). Whilst shallow-substrate Sedum roofs can provide greater biodiversity value than a standard unvegetated (grey) roof, biodiversity benefits can be greatly increased by using more diverse floral mixes.

Figure 2. Biodiverse (biosolar) roof in London's Queen Elizabeth Olympic Park. *The roof was designed to contribute to targets for Open Mosaic Habitat creation in the Olympic Park Biodiversity Action Plan (BAP). Image © Stuart Connop*

Waterproofing**:** Most waterproofing solutions are suitable for a biodiverse roof system. However, the waterproofing needs to be robust enough to tolerate any mechanical damage from the biodiverse roof construction. Waterproofing should be carefully detailed and thoroughly checked for any potential leaks prior to installation of any green roof.

Other technical considerations: The ecological value of biodiverse green roofs can be greatly enhanced by adding habitat features such as deadwood, sand, pebble/rubble mounds. These increase structural diversity and can provide refugia, nesting, and basking opportunities. Artificial bee and insect hotels can also be added. In terms of roof construction, flat and low-pitched roofs are most suitable. For biodiverse roofs, long-term maintenance and monitoring should be considered early in the design process, and therefore suitable edge-protection or a 'mansafe' fall protection system will need to be factored into the design.

In terms of stewardship, a light touch management/maintenance regime is often preferred. Unless irrigated in times of drought, the vegetation will tend to die back, which can be beneficial in reducing grass dominance on a roof and retaining a diversity of wildflowers through regeneration from the seed bank within the substrate. However, there may be a need to reintroduce some species if no viable seed is present. In general, a mechanism to irrigate the roof in times of drought can be beneficial, both in terms of maintaining a floristic source of pollen and nectar for pollinators and reducing fire risk. Ideally, irrigation should use a mosaic approach, with some areas watered and others not, as this method can be the best for balancing short and long-term biodiversity value and sustainability.

Maintenance for biodiverse roofs typically involves visits once or twice a year for basic tasks such as removal of invasive species and keeping drainage outlets free of debris. It is recommended that maintenance includes an autumn visit to cut and remove any build-up of vegetation in areas where it is undesirable. Strimming and removal of vegetation should be carried out to maintain a fire break of 300 mm width around perimeters and penetrations (i.e. rooflights, soil pipes, rainwater outlets etc). This should be increased to 500 mm where there are openings to buildings to act as a fire break between the green roof and the building. It should be noted that, on biodiverse roofs, some standing seed heads represent a valuable resource for many over-wintering insects. As such, where this does not pose a fire risk, seed heads should be left uncut. For more specific information on maintenance see the GRO guide (GRO, 2021). Maintenance should be coupled with basic monitoring to assess that the roof is continuing to deliver the benefits for which it was designed. This can be supplemented with more comprehensive surveys by a suitably qualified ecologist to record key species/groups using the roof. As the roofs are designed primarily for biodiversity, it may be necessary to restrict access to the roof to keep disturbance to a minimum.

Sustainable Drainage Systems (SuDS)

Green roofs can be installed as a SuDS solution to help manage flooding and stormwater control. They have been demonstrated to both lower (attenuate) and delay the peak runoff (Berndtsson, 2010) in storm events. Retention between 25 and 100% can be achieved (DeNardo *et al.*, 2005; Getter, Rowe and Andresen, 2007; Zheng *et al.*, 2021) with performance dependent upon the level of saturation of the substrate and drainage layer at the start of the storm event (Ercolani *et al.*, 2018). A green roof will reduce the amount of water run-off by holding water in the plants, substrate and drainage layer, some of which will be released back into the atmosphere via evaporation/evapotranspiration and any excess water released at a slower rate, to reduce pressure on terrestrial drainage systems (see GRO, 2021). This reduction can be considerable when deeper substrates are installed and/or when drainage layers with substantial storage volume are included. However, the potential for reduction is related to the saturation of the substrate and drainage layer at the time of the storm event. As such, SuDs performance can be variable (Zheng *et al.*, 2021). Nonetheless, even when saturated, such roofs can provide some benefit in terms of delaying runoff into the storm drain system (Akther *et al.*, 2018). Blue roofs are an alternative SuDS method that includes a void space within the drainage that holds stormwater, which is then slowly released over a 24-hour period via a control valve. Blue roofs can be designed with a vegetation layer and these are sometimes called a blue/green roof (GRO, 2021). Such roofs, typically have greater storage capacity that standard green roofs (NFRC, 2017), and can be combined with smart technology linked to meteorological data to empty when heavy rain events are expected (RESILIO, 2020).

In addition to water storage and delay, green roofs have the potential to influence the water run-off quality from the roof (Buffam, Mitchell and Durtsche, 2016). As the majority of green roofs are rainwater fed, there is potential for a decrease in water quality, for example, due to increased nitrogen loading leaching from the roof substrate. However, if there is opportunity to divert other sources of urban run-off to the roof, there is also the possibility for improving water quality.

Building constraints: Buildings with a loading capacity <100kg/m^2 have limited value for SuDS storage. However they do tend to dry out faster after rainfall events, and therefore any recharge volume they do have would become available more quickly (Schultz, Sailor and Starry, 2018). Loading capacities between 150 and 250kg/m^2 allow for greater volumes of water storage, and this includes blue-green roof systems with more substantial storage capacities. Loading >250kg/m^2 would enable a substantial blue roof system to be installed beneath a green roof, or allow inclusion of standing water such as a pond as part of a green roof system. The deeper build-up of a blue/green roof means that building height constraints can limit what can be achieved. Most blue roof systems will require a zero fall (flat) roof. The stormwater run-off retention will generally be reduced where the slope is higher (Bengtsson, 2005; Getter, Rowe and Andresen, 2007).

Drainage: For SuDS roofs the key aim is to maximise short-term water storage with controlled release to avoid storm drain systems becoming overloaded during storm events. Drainage elements such as gravel or porous, free-draining substrates are suitable. However, the weight of saturated substrate 120kg+ per 100mm may cause issues on lighter roof systems. Where standard drainage layers are used, these can range from the 25mm deep drainage boards that are typically used on lighter weight roofs (<100kg/m^2), to drainage layers up to 40-50mm deep. Blue-green roof drainage systems can be designed so they combine a standard green roof drainage board (including planned accessible storage) with an additional water storage component that is not accessible to the vegetation layer. This second storage volume is linked to either a controlled-release system (that slowly releases stored water to the terrestrial drainage system), or a smart technology system that uses meteorological data and releases stored volumes prior to a predicted heavy rainfall event, so that full storage capacity is available.

***Substrate*:** For SuDS roofs, deeper substrates with good void ratios will increase water storage capacity and benefit SuDS performance (London Borough of Tower Hamlets, 2014; CIRIA, 2017; BSI, 2019). Deeper specialist substrates will improve water-holding capacity. These are unlikely to be more than 50% void compared to 95% for blue roof voids. It is recommended to avoid substrates that contain a high proportion of fine particles. These can develop a hard ‘crust’ during the dry summer months and can reduce permeability and performance during this critical period for SuDS (see BSI, 2019 for guidance).

Vegetation: Vegetation can play a key role in intercepting and delaying run-off during storm events. Nonetheless, the volume of water taken up by the vegetation is not typically considered as a factor in SuDS. With green roofs there is a complex relationship between the vegetation and the substrate layers. Roofs with greater vegetation cover will potentially result in greater water usage from substrate and drainage layer through evapotranspiration, but can also create more shading of the substrate resulting in a reduction of evaporation these layers (Stovin *et al.*, 2015). Due to the complexity of this interrelationship, vegetation is not typically considered as part of the attenuation strategy.

Although other green roof types (e.g. biodiverse, biosolar, recreation) can provide significant SuDS performance, green roofs installed with a sole focus on SuDS performance are often sedum systems. Historically, sedum systems have been the most popular form of green roof. Sedum species tend to be hardy and drought tolerant, making them perfectly adapted to growing in the harsh exposed conditions on a roof. As most sedums are evergreen succulents they can give a neat, low growing carpet-like covering to a roof. Whilst popular and hardy, most of the sedum species used on green roofs are non-native, and the use of this single plant group and its limited flowering period mean sedum systems would not always meet planning and biodiversity goals. In addition, sedum roofs can be substantially less able to retain water than for example grass roofs (Mickovski *et al.*, 2013). Sedums are, however, well adapted for use on shallow substrate SuDS roofs due to their ability to cope with prolonged dry periods, and thus maximum recharge volumes in the green roof substrates and drainage boards.

Waterproofing: For any green or blue roof that will delay the flow of rainwater from the roof, the most robust and reliable waterproofing will be required, such as bituminous membranes or hot-melt systems. Inverted blue roof systems are not suitable as this may increase the U-Value due to the insulation losing its effectiveness when wet, or if the inverted insulation floats when the roof is saturated.

Other technical considerations: True blue-green roofs will require a flat roof designed with zero falls and no back falls. This would ensure even spread of the load from the stored water. Calculations to confirm the flow rate and the depth of water (H-Max) are needed to meet SuDS requirements. Rainwater outlets from the roof must be fitted with control mechanism to restrict the flow and the design must ensure that sufficient overflows have been provided in case capacity is exceeded.

Access to the roof will be required to inspect and maintain the system and edge protection or man-safe systems would therefore be needed. In terms of stewardship, maintenance would be similar to that for biodiverse roofs, typically with two visits per year to remove non-target plant species and leaf debris. Maintenance would need to particularly focus on clearing drainage outlets, inspection chambers, and shingle/gravel perimeters (GRO, 2021). For maintenance visits of blue and blue/green roof systems restrictor chambers, orifices and roof outlets should be inspected and particle filters cleaned or replaced when necessary (GRO, 2021).

It is possible to use the run-off rainwater from a green roof, mainly for non-potable purposes, such as flushing toilets or irrigation. Where the rainwater is used for irrigation, basic filtration may be required to remove dirt and particles. If rainwater run-off is redirected for use to flush toilets or wash clothes, a more advanced filtering system would be needed.

Consideration of green roof maintenance and management is also important in relation to water quality targets. Generally, green roofs reduce the heavy metal content of stormwater run-off for lead, zinc, cadmium or copper. Conversely, green roofs may increase the quantity of phosphorous in the run-off, although this can reduce with time and nitrogen concentration values vary (Berndtsson, 2010; Berardi, GhaffarianHoseini and GhaffarianHoseini, 2014). To reduce impacts on phosphorous and/or nitrogen loading, it is best to minimise or avoid the use of fertilisers on green roofs. Conventional fertilizers cause higher nutrient concentrations in runoff water than controlled release fertilizer, and consequently the latter is preferable if fertiliser use on a green roof is absolutely necessary (Berndtsson, 2010).

Recreational space/urban agriculture

Green roofs can be installed to deliver recreational value, which can range from providing purely visual amenity for overlooking adjacent spaces/buildings, to a fully accessible outdoor garden, park or food growing space (GRO, 2021). Green roofs in urban locations can provide a form of elevated garden and offer a range of social benefits, such as the visual aesthetic value of the garden for visitors or overlooking properties, as well as a quiet space away from ground-level traffic noise and pollution (Kotzen, 2018). Green roofs have been linked with broad social benefits, including psychological benefits (Williams *et al.*, 2019), social cohesion, and local food production/food security (Shafique, Kim and Rafiq, 2018).

***Building constraints*:** Buildings with a loading capacity <250kg/m^2 offer limited opportunities for recreation beyond the aesthetic value for those with views overlooking the roof. With loading capacities of between >250kg/m^2 and 350kg/m^2, the opportunities can be somewhat expanded to occasional visits by individual/low numbers of people to observe the roof or undertake low frequency activities such as attending to hives for bee-keeping. Roofs with loading capacities >350kg/m^2 offer the broadest opportunities for recreational roofs as these can permit access by groups of people, for instance for urban agricultural pursuits, and can support more formal landscaping such a roof gardens (Figure 3). Greater loading capacities are needed for public access and the roof fall construction must be 1:40 or less.

Figure 3. Roof garden in West End of London that is used as an amenity space by office staff in the building. *Image © Caroline Nash*

Drainage: The drainage board should typically cover the whole roof area, allow water to drain freely and have good compressive strength to support hard and soft landscaping. The drainage layer would need a long design-life and be deep enough to absorb deflection in slabs.

Substrate: For a recreation green roof the substrate should be chosen to match the vegetation required and should comply with GRO code (GRO, 2021) and FLL guidelines (FLL, 2018). For example, different growing media would be required for lawns, ornamental plants and allotment areas. Where weight reduction is required, void formers can be used in the build-up.

Vegetation: There is potential to use a broad diversity of vegetation on a recreational green roof, from wildflower areas to more ornamental planting including shrubs and trees. For roof-top food growing projects, it may be sufficient to provide the substrate, and allow the growers to supply their own seeds or plants. Nonetheless, the intended type of vegetation would have considerable implications for the depth and weight of the system, so must be considered in relation to loading capacity and substrate type.

Waterproofing: For deep intensive green roofs, the most robust waterproofing should be specified as once constructed, gaining access to the underlying waterproofing layer would be very difficult. Bituminous membranes and 'hot melt' systems are generally used for this type of green roof. Given the typically longer lifecycle of an intensive recreational roof system, the waterproofing would also need to carry a warranty for an extended period.

Other technical considerations**:** Green roofs that provide a recreation space generally have additional maintenance requirements compared to other green roof typologies. This is to ensure that the soft and hard landscaping remains in good condition, meets with the aesthetic requirements for the project, and any slabs remain secure. When lawns are provided these typically would be regularly mown, and ornamental planting areas maintained and weeded. Intensive recreation green roof options typically require a permanent irrigation system to keep vegetation in optimal condition. For rooftop allotment projects, rainwater harvesting systems can offer a sustainable option for irrigation, although this too may result in energy consumption if a pump is required (unless solar energy can be harnessed to power a pump). As this type of roof typically needs to be accessible to users, level access and perimeter edge protection at roof level are required for health and safety.

For urban agriculture projects, there is also a need for ongoing care and harvesting of crops. As with biodiverse and SuDS roofs, undesirable vegetation should be removed. Failed plants that are integral to the design of the roof should be replaced, as should eroded substrates (GRO, 2021). As with other green roof systems, drainage outlets, inspection chambers, and perimeters should be cleared of vegetation.

Biosolar

Biosolar roofs are a relatively recent development in broadening the multifunctional benefits that can be provided by green roof systems. Biosolar roofs combine green roofs (bio) with photovoltaic (solar) panels, enabling the two technologies to be installed together on a roof, rather than competing for roof space. This design adds green renewable energy as an additional benefit for green roof installation. By impacting the local microclimate, green roofs appear to create more optimal operating temperatures for photovoltaic panels than standard grey roofs, thereby enhancing their energy efficiency. Research has shown that installing photovoltaic solar panels on a green roof can improve the energy production performance of the photovoltaic panels by, typically, 1-6% (Köhler et al. 2007; Perez et al. 2012; Nagengast et al. 2013; Chemisana & Lamnatou 2014; Shafique et al. 2020). This is due to the improved performance of photovoltaic panels at lower temperature. In addition, there is an indication that PVs can contribute to enhancing microclimates and habitat complexity when combined with biodiverse roofs (Nash et al., 2016 and **Figure 4**) and Sedum green roof systems (Köhler et al., 2007; Bousselot et al., 2013) creating a 'symbiotic' relationship between the green roof and the photovoltaic panels.

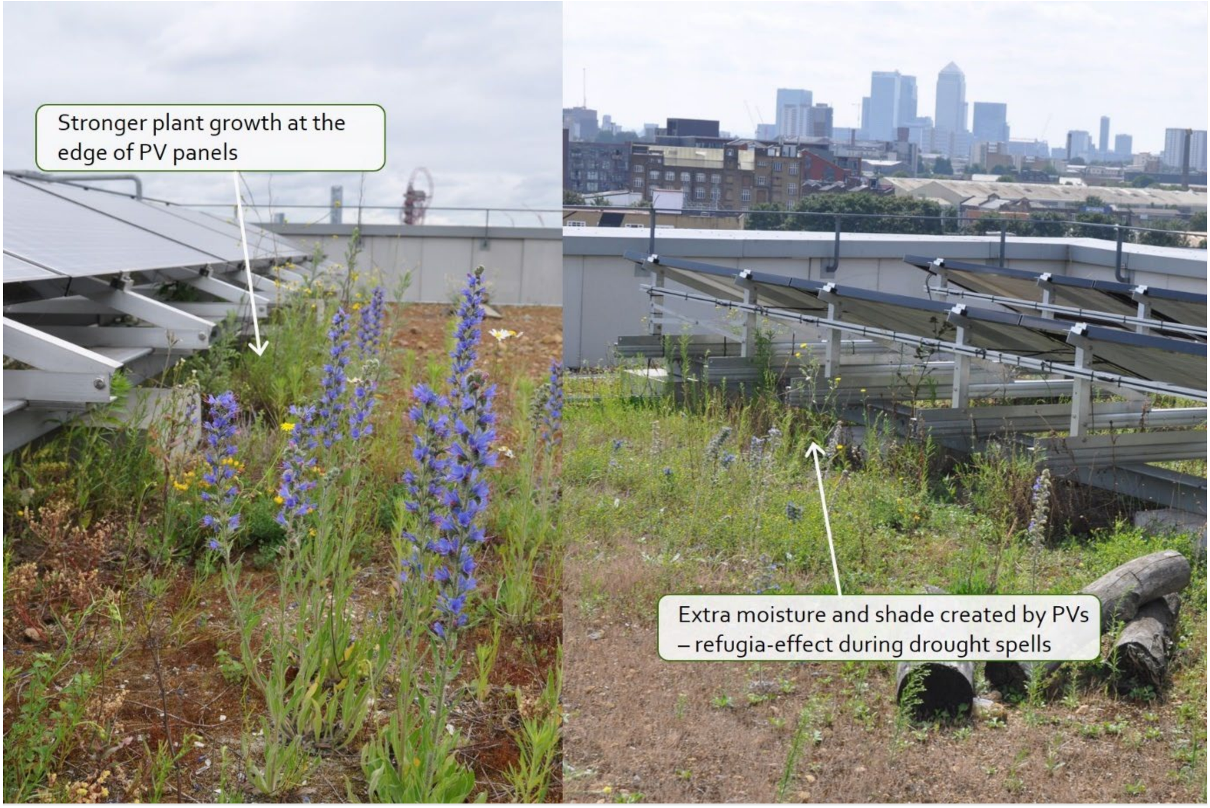

Figure 4. Example of biosolar biodiverse roof in London's Queen Elizabeth Olympic Park. *Images illustrate how PVs create shade/moisture microclimates that contribute to habitat complexity. Images © Caroline Nash*

Building constraints: Biosolar roofs will involve an additional load, the magnitude of which would depend on the type of solar PV module system installed. For instance, ballasted installations could add a significant extra weight load, whereas newer non-penetrative and lightweight PV mounting systems add as little as 4-5 kg/m^2, depending on the modules. Building height constraints may represent a barrier as PVs are typically installed as mounted angled arrays, and thus, typically, increase the height of the roof. Safe access is required for maintenance and servicing of the arrays, but this may present challenges in relation to installing a 'mansafe' fall protection system around the PV array and green roof elements. Wind load uplift calculations should be carried out to ensure the system is secure. This is particularly important on high buildings and/or exposed locations.

Drainage: Typically, a drainage layer should be installed over the entire roof area with both the PV and biodiverse roof incorporating this into their design. The drainage layer construction can be the same type as used for other systems, incorporating either a standard or blue/green system.

Substrate: For a ballasted biosolar roof installation the substrate depth will vary with the weight required to prevent wind uplift. Biosolar roofs can utilise biodiverse green roof design principles – using varied types and depths of substrate. The solar panels offer an opportunity to add topographical variation of substrates which can enhance SuDS and biodiversity benefits. For lightweight biosolar systems, the substrate and vegetation can provide the ballast to secure the array. Substrates need to comply with GRO code (GRO, 2021) and FLL guidelines (FLL, 2018).

Vegetation: As vegetation can optimise the efficiency performance of PVs through its evaporative cooling, consideration of this component is critical. The vegetation around the array should be a mixture of low-growing species that will not shade the panels and should include shade-tolerant species that can establish in shady niches created by the solar panels. Depending on the density of solar panels being installed, the shade-tolerant component of the plant palette may need to be increased. The displacement of rainwater by the PV panels creates run-off 'moisture zones', adding hydrological diversity that can increase plant species richness (Nash *et al.*, 2016). The array layout can therefore provide opportunities to create vegetation mosaics related to the sun/shade and moisture gradients provided by the PVs. High-density arrays may, however, significantly inhibit plant growth, reducing any evaporative cooling effect from the vegetation.

Waterproofing: A key consideration for waterproofing a biosolar roof is to avoid any penetration of the waterproofing layer from anchoring the PVs. Ballasted systems that avoid penetration are therefore preferable in this respect, and lightweight options are now available.

Other technical considerations: Biosolar roofs are generally installed on flat or low-pitched roofs. To optimise the symbiotic relationship between the PVs and the vegetation, the system must be designed with technical consideration for both elements. Maintenance specific to biosolar roofs may involve vegetation management to avoid excessive shading of PV panels if tall, dense plant growth occurs. Typically, regular irrigation of biosolar roofs is not recommended as the additional water can cause vigorous vegetation growth, leading to shading of PVs and potentially inhibiting their effectiveness. Nonetheless, watering during droughts can benefit vegetation performance and reduce fire risk, and ideally water sources such as water harvesting/grey water recycling should be used rather than mains water, to improve the sustainability of the system. In relation to fire risk, as with other green roof systems, maintaining the organic proportion of the substrate below 20% will reduce fire risk.

Carbon/energy efficiency

A green roof can be installed to contribute to the energy and carbon efficiency of a building. Whilst this is not a commonplace driver for green roof installation presently, it is likely to become increasingly important to understand the carbon lifecycle and benefits as we commit industries to net-zero carbon emissions targets. By doing so, it will be possible to add this component, or balance any carbon-cost, against the other ecosystem service benefits associated with green roof creation.

Green roofs can contribute to reducing CO_2 emissions in buildings in three core ways: first the green roof can result in energy savings from improving heat transfer through the roof, thereby reducing the heating demand or cooling demand of the building. Secondly, the green roof can sequester carbon naturally through photosynthesis and into the substrate. Thirdly, atmospheric carbon can be embodied into specialist green roof production materials (Gunning, Hills and Carey, 2009). Conversely, installing a green roof can result in additional carbon emissions due to the embodied carbon in the materials that are used to build it, as well as the substrate and irrigation materials (Rowe, 2011).

Building constraints: The embodied carbon of a building component is the carbon emissions released through its lifecycle, including raw material extraction, fabrication, manufacture and transport. The embodied carbon of a green roof tends to be above that of a conventional roof (Kosareo and Ries, 2007; Rowe, 2011). Various tools can be used to calculate the embodied carbon of a green roof, including BRE IMPACT Tools, ETool, the ICE database, and more. These tools use databases which contain data on embodied carbon emissions for various materials, and use the quantity of materials (in volume or weight) to calculate the embodied carbon of the whole roof system. The carbon emissions implications of maintaining a green roof system should be included in the lifecycle analysis.

The embodied carbon of green roofs is substantial. For example, the embodied carbon of a green roof has been calculated to be 23.6 kg CO^2 per square meter of green roof (or 6448 g C m^2), assuming a generic industry root barrier, drainage layer, and 6.0 cm of substrate consisting of half sand and heat expanded slate by volume (Hammond and Jones, 2008; Rowe, 2011). Comparable results on an irrigated modular extensive green roof were found at 25.2 kg-CO2·m^{-2} (Kuronuma *et al.*, 2018), reducing slightly to 24.6 kg-CO2·m^{-2} without the irrigation system.

Drainage: A drainage layer made from natural or local materials such as a pebble drainage layer can contribute to energy/carbon efficiency, and consideration should be given to the material's long-term durability and disassembly. Organic components such as straw should be avoided as these have a short life span, unless these are the only solution in situations when only very lightweight roofs are possible. Calculations of the embodied carbon of drainage layer products can be carried out and use of recycled and recyclable plastic materials can be beneficial.

For heavy green roofs in new-build situations there is potentially an indirect increase in embodied carbon attached to the additional weight from the roof, and the consequent increase in the structure of the building. Alternative drainage materials can present benefits in terms of the weight of the green roof and will also likely have a lower embodied carbon impact. For example, basalt gravel, recycled rubber, recycled high-density polyethylene (HDPE) trays, and recycled polyethylene terephthalate (PET) bottles respectively weigh 175, 118, 70 and 49 kgf/m², offering a reduction of up to 72% in weight per area, thereby reducing the impact on the structure of the building (Naranjo *et al.*, 2020). The disposal of the green roof also will impact on its life-cycle CO_2 impact (Kuronuma *et al.*, 2018).

Metal edge trims must also be accounted for, as some metals such as virgin aluminium can have a high impact, due to the high embodied carbon of the material itself. Comparably, recycled aluminium has an embodied carbon almost ten times lower.

Substrate: The substrate can represent a high proportion in the overall carbon cost of the green roof due to its substantial part of the whole in weight and volume. Using recycled products in substrates, for example crushed reject brick, ceramics, and green bin waste can help with carbon/energy efficiency targets. Using local suppliers to reduce transportation miles of all components has an impact on embodied energy. It is possible to use aggregates that have a negative net-carbon cost (e.g. Carbon8 aggregates that lock away CO2 during production). Peat-based substrates should always be avoided both due to the carbon cost, and broader impacts of peat extraction (Lindsay, Birnie and Clough, 2014).

Vegetation: Different plants on green roofs lead to significant variations in the thermal insulation value of the roof. For instance, the R-Value of a sedum green roof was found to be was twice that of a rye grass green roof at 40°C for the same build-up (Cox, 2010).

The foliage of the plants can act as a shading device on the roof, where it absorbs part of the solar energy for photosynthesis. The space under the foliage transfers heat by convection and radiation to the roof underneath. Together the substrate and vegetation cause evaporative and evapotranspiration cooling to the surface of the roof, lowering the temperature (Berardi, GhaffarianHoseini and GhaffarianHoseini, 2014; Coma *et al.*, 2014). Plants with a high leaf coverage will therefore tend to cause an increase of energy consumption in winter and a reduction in summer, as they reduce solar heat gains (Sailor, 2008). Green roofs reflect between 20% and 30% of solar radiation and absorb up to 60% of it through photosynthesis (Berardi, GhaffarianHoseini and GhaffarianHoseini, 2014) and can cool as effectively as the brightest possible white roofs, with an equivalent albedo of 0.7–0.85 (Gaffin *et al.*, 2010).

Carbon will be naturally sequestered in the green roof vegetation through photosynthesis and in the substrate from the plant waste and exudates from their root system (Rowe, 2011). This can have a significant impact on the lifecycle carbon of the roof overall. For example, a study on extensive green roofs in the United States estimated that the carbon sequestered by growing biomass shortened the carbon payback period from nine years to seven (Getter *et al.*, 2009). However, there are extremely wide differences in the amount of carbon sequestered depending on studies, with values as low as 162 g C m^{-2} yr^{-1} (Getter et al., 2009) and as high as 65 kg C.m^{-2} yr^{-1} (Whittinghill et al., 2014). Larger above ground biomass, more woody structures, and a deeper substrate will achieve the best carbon sequestration. Sun exposure and irrigation will also have an impact (Getter *et al.*, 2009; Whittinghill *et al.*, 2014; Kuronuma *et al.*, 2018). However, the length of time that carbon remains in a green roof is uncertain. Where plants die back or are cut back annually, the decomposition of this dead material can mean that the carbon sequestered is then released back as CO_2 (Whittinghill *et al.*, 2014). If the production of plants exceeds decomposition, then the ecosystem is a carbon sink overall (Li and Babcock, 2014). Whilst initially the green roof vegetation will typically serve as a carbon sink, eventually the green roof may reach a carbon equilibrium where carbon assimilation will equal carbon decomposition (Rowe, 2011).

To minimise wider carbon trade-offs, plants should not be sourced from nurseries that use peat-based compost. From a purely carbon calculation perspective, it is typically beneficial to seed a roof rather than use plug plants or pre-seeded mats. Irrigation also typically results in carbon emissions and consequently, rainwater harvesting or greywater recycling can help reduce carbon impacts if a pump is not required or if it is driven by renewable energy. The best option is to rely on natural processes of drought and recolonisation and use drought-resistant plants to minimise irrigation requirements.

Waterproofing: Ideally a comparison of the embodied carbon of waterproofing options should be undertaken to select the most efficient product. Single-ply Polyvinyl Chloride (PVC) and Ethylene Propylene Diene Monome (EPDM) are widely used to waterproof roofing but have high embodied carbon, and PVC has additional negative environmental impacts that should be considered (e.g. toxic additives that can leach). The synthetic Thermoplastic Poly Olefin (TPO) and Flexible Poly Olefin (FPO) membranes have a low embodied carbon impact. Alternatively, bituminous membranes can provide a suitable alternative from the point of view of embodied carbon and may also be more economical (Gonçalves *et al.*, 2019).

Other technical considerations: Calculating the impact of a green roof on the thermal performance of a building is complex and requires the use of dynamic thermal analysis software. A steady state calculation would not represent accurately the thermal inertia behaviour of the roof. Whilst there have been attempts to create a model that provides a U-Value for green roofs these will not represent the shading and cooling effects of a roof accurately. An algorithm to accurately model the thermal performance of green roofs has been developed that has been integrated into Energy Plus software and validated using data collected from a green roof (Sailor, 2008). In addition, a model is available for Honeybee that represents the performance of green roofs (Mackey, 2017).

The low solar absorbance of green roofs as well as evapotranspiration and the reflectance from the vegetation result in a reduction of cooling demand for buildings or improvements to summer comfort. The thermal mass of the green roof additionally stabilises the temperatures both in winter and summer (Saiz *et al.*, 2006; Castleton *et al.*, 2010; Jim and Tsang, 2011; Cubi *et al.*, 2016). As moisture content will influence the thermal conductivity of the growing medium, this will also have an impact on the thermal performance (Cubi *et al.*, 2016).

The energy use reduction impact of green roofs is often much more significant in terms of the cooling demand than in terms of the heating demand (Saiz *et al.*, 2006; Ascione *et al.*, 2013). In winter, the thermal transmittance can be the most important parameter to determine the heat transfer (Coma *et al.*, 2014), and consequently, the green roof will influence the heat balance less strongly.

The cooling and heating potential of green roofs vary strongly depending on the climate (La Roche and Berardi, 2014). A study of green roofs in Europe found that in warm climates such as in Tenerife, Sevilla and Rome, the energy demand was reduced by up to 11%, whereas in cold climates, annual savings were up to 7%, with savings between 4% and 7% in London (Ascione *et al.*, 2013). With increasing temperatures in cities due to the urban heat island effect and climate change, high summer temperatures and heat waves are increasingly likely in the UK and should not be discounted (Castleton *et al.*, 2010). Various simulation studies suggest that green roofs may be able to reduce average ambient temperature by 0.3 to 3K when applied at a city scale (Santanamouris, 2014).

The energy savings that a green roof creates in terms of cooling and heating do, over the lifecycle of the roof, often overcome the embodied carbon cost from the materials of the roof itself (Cubi *et al.*, 2016). However, crucially, where a roof has significant levels of roof insulation, the thermal benefit of the green roof will be much smaller (Castleton *et al.*, 2010). If the green roof is above a well-insulated roof, then the green roof energy balance would be decoupled from that of the building, and the green roof will have an impact on the urban environment (Berardi, GhaffarianHoseini and GhaffarianHoseini, 2014). Consequently, in terms of thermal performance of retrofitted roofs, green roofs tend to be more beneficial on buildings with initially poor insulation installed (Castleton *et al.*, 2010). As building energy regulation increasingly requires substantial insulation on new buildings, the impact of green roofs on the internal conditions therefore decreases.

If a primary objective is to reduce carbon emissions, then the use of a biosolar roof can provide higher carbon reduction, albeit at a higher cost (Cubi *et al.*, 2016). The cooling effect of a green roof on the photovoltaics can improve their performance (see above biosolar section).

Other green roof motivations and types

The above examples cover the more common motivations and categories of green roof that are likely to be considered for development projects. The following section gives a brief overview of some additional specialised green roof applications, which may cross over with other landscaping/green infrastructure approaches (e.g. green bridges), but could equally be termed green roofs given their construction principles.

Environmental masking: Green roofs can be installed to help blend a building into the surrounding landscape and to help mitigate the loss of permeable land surface to the building. Green roofs for environmental masking are often installed on pitched or profiled roofs. Profiled roofs with slopes >5° would typically need mechanical restraint at the base and substrates are normally unstable on roofs sloped >25-30°. The vegetation would typically need to strongly reflect the species in the surrounding habitat to achieve blending, and substrates and drainage would need to be appropriate to support the vegetation. Whilst vegetation similar to the surroundings can establish on a roof, the conditions at roof level will generally be different to the surroundings. For instance, the roof vegetation would be likely to dry out more quickly, and thus may require a different maintenance regime to the surrounding habitat. Establishing vegetation from seeds and plug plants can be challenging on roofs with steep pitches and maintenance can be more challenging on roofs with a pitch too steep to walk on (i.e. 25°+). Waterproofing selection would need to be suitable for the structure of the building. Ideally, the building design should be sympathetic to the environment, to help masking and sustainability.

Green bridges: Green bridges are structures built to enable wildlife to cross landscapes that have become fragmented by transportation infrastructure such as roads and railways (Landscape Institute, 2015; Natural England, 2015). The motivations align with those for biodiverse roofs and environmental masking; the bridges are intended to provide habitat for wildlife, to reduce habitat fragmentation and restore connectivity/permeability for biodiversity by facilitating movement, and present an opportunity to mask, to some extent, the hard engineering of the bridge and surrounding transport infrastructure. Installing greenery on a bridge involves many of the same technical requirements as construction of an intensive green roof, and therefore most of the technical considerations set out in the 'recreational roof' section above would be applicable for a green bridge project. This book also contains a dedicated chapter on green bridges (see Chapter ? for more detail).

Green capping: Whilst not strictly an engineered green roof solution, green ('soft') capping of historic walls and ruins has parallels with green roofing. Turf/vegetation and soil are used to protect wall tops/ruins and the underlying masonry and stonework from heating, cooling and freeze-thaw weathering (Wood, Cathersides and Viles, 2018), in much the same way that green roofs can help protect and prolong the lifespan of a building roof. As this is a relatively novel research and specialist area with fairly unique engineering requirements, the following resources are recommended as a starting reference point for a project of this nature (Naylor *et al.*, 2017; Wood, Cathersides and Viles, 2018).

Noise regulation: Green roofs can also provide valuable sound insulation as well as sound absorption. The transmission of the sound can be particularly reduced for low frequencies (5 to 13dB) (Connelly and Hodgson, 2008). Green roofs are able to absorb noise, and it has been shown that they can reduce the noise levels in an urban area by shielding from traffic noise. This effect will be reduced when the green roof is saturated with water (Van Renterghem and Botteldooren, 2014).

Planning requirements and sustainability certification

Public policies are fundamental to stimulating the adoption of sustainable strategies that promote green infrastructure, including green roofs, to create greener cities (Liberalesso *et al.*, 2020). Many policies worldwide are encouraging more sustainable buildings, often through the application of green roofs, and do so at the city level. For example, a law in Tokyo requires the installation of green roofs on at least 20% of the total roof area for large buildings. In Germany, green roofs installation is incentivised through financial benefits. For example, in Esslingen in Germany, 50% of the cost of a green roof is refunded, while in Darmstadt the installation of a green roof results in reimbursement of 5000 euros (Berardi, GhaffarianHoseini and GhaffarianHoseini, 2014).

UK national and regional policies: Planning conditions for green roofs are typically related to requirements for meeting biodiversity targets. Therefore, much of the technical considerations set out for biodiverse roofs would apply to this scenario (e.g. native species not Sedum, and suitable substrate depths for vegetation). In the UK, several national policy documents encourage developers to include green roofs in building design, such as:

- Biodiversity 2020: A strategy for England's wildlife and ecosystem services (DEFRA, 2020) encouraged developments that reinforces biodiversity and improves wildlife habitats, in urban contexts and within the built environment.
- Section 40 of the Natural Environment and Rural Communities Act 2006 places a duty on all public authorities in England and Wales to conserve biodiversity (Parliament, 2006).

- 'The Natural Choice: securing the value of nature' white paper (HM Goverment, 2011) established a commitment to applying the concepts of 'ecosystem services' through provision of green infrastructure such as green roofs for buildings and new developments.
- Section 15 of the National Planning Policy Framework (Ministry of Housing, Communities and Local Government, 2021), "Conserving and Enhancing the Natural Environment", encourages the incorporation of biodiversity improvements in and around developments and indicates that plans should take a strategic approach to maintain and enhance networks of habitat and green infrastructure.

London and other local policies: In London, the pioneering Living Roofs and Walls Policy (Grant and Gedge, 2019) was first introduced into the London Plan (Greater London Authority, 2021), the spatial development strategy for London, in 2008. Since then, the uptake of green roofs has rocketed across London, and as of 2017, the total area of green roofs in the Greater London Area was 1.5 million m², and 290,000 m² in the Central Activity Zone (Grant and Gedge, 2019).

The latest London Plan (Greater London Authority, 2021) includes an Urban Greening Factor (UGF) which will help London boroughs to define a minimum amount of greening to be included in new major developments. The London Plan demands that boroughs should define an UGF and recommends an UGF of 0.4 for residential developments, and a target score of 0.3 for commercial developments. The Urban Greening Factor will be calculated as follows: (Factor A x Area) + (Factor B x Area) + (Factor C x Area) etc. divided by Total Site Area.

The "Factors" correspond to the green element typology, and green roofs that meet the GRO code (GRO, 2014, 2021) have a particularly favourable Factor:

- An extensive green roof with substrate of minimum settled depth of 80mm (or 60mm beneath a vegetation blanket) that meets the requirements of the GRO Code have a Factor of 0.7
- An intensive green roof or vegetation over structure with a substrate minimum settled depth of 150mm have a Factor of 0.8
- An extensive green roof of Sedum mat or other lightweight systems that do not meet the GRO Code have a Factor of 0.3
- For comparison, mown grass has a factor of 0.4.

Several local London boroughs have also adopted green roofs policies. For example, the London Borough of Lewisham has adopted a green roof policy in their UDP, and the Lewisham Biodiversity Partnership has drafted a Green Roof Action Plan (DEFRA, 2002), London Boroughs have also promoted green roofs in other green infrastructure guidance (e.g. London Borough of Barking and Dagenham Green Infrastructure and Biodiversity Strategy (London Borough of Barking & Dagenham, 2019) and Tower Hamlets Sustainable Drainage Systems Guidance (London Borough of Tower Hamlets, 2014).

Outside of London, some local councils have also integrated green roofs requirements for development. For example, Sheffield City Council requires for all large developments to have green roofs that cover at least 80% of the total roof area (Sheffield City Council, 2011).

Sustainability assessment schemes: In addition to policy drivers, green roofs are often implemented to support the process of receiving assessment certifications for sustainable buildings (Berardi, GhaffarianHoseini and GhaffarianHoseini, 2014). Environmental assessment methods are used to evaluate the sustainability credentials of a building or community, using a range of criteria arranged in categories such as water, energy, pollution, materials and land use and ecology. In most cases, points can be achieved for each criterion, and these are then added, sometimes using weighting systems, to form a total score that corresponds to a final environmental performance rating. The building or community is awarded a certificate or award which will relate to its sustainability performance rating.

Internationally, the LEED (Leadership in Energy and Environmental Design) system is widely used. There are other systems around the world such as Green Star in Australia, Estimada in the Middle East and the DGNB (Deutsche Gessellschaft fur Nachhaltiges Bauen) certification system in Germany. BREEAM is the most commonly used certification system in the UK, along with its housing certification scheme – the Home Quality Mark. Awards ratings range in order of performance from Fail, Pass, Good, Very Good, Excellent or Outstanding, the latter being particularly challenging to achieve.

Whilst green roofs are not directly integrated as a requirement within BREEAM or LEED, they can help to achieve points in many of the criteria for both systems. Green roofs have been identified as a key component needed to achieve the highest rating levels for such certification schemes (Szecsödy and Lilja, 2020). This is particularly the case for BREEAM where green roofs score points in many areas (Naranjo et al, 2020). Higher ratings under these programs can lead to higher market and rent value for properties, as well as reduced vacancy (Szecsödy and Lilja, 2020).

In the UK, achieving a minimum BREEAM score is often a requirement of high-profile clients and for public funding bodies (Parker, 2012). The Government Construction Strategy (The Infrastructure and Projects Authority, 2016) requires an environmental assessment to be carried out for all public projects, with an aim to achieve BREEAM "Excellent" rating for new buildings and "Very Good" for refurbishments, or equivalent. In addition, local authorities often require that a minimum BREEAM certification level is achieved as part of a local plan or as a planning condition. There can, however, be substantial local differences, for example, Doncaster Metropolitan Borough Council requires developers to hit BREEAM's Very Good rating while Camden Council have a BREEAM requirement of Excellent, with specific requirements in some categories.

Table 3 below presents the main relevant credits for BREEAM and LEED New Construction codes related to green roof installations.

Table 2. Examples of potential credits that can be gained by installing a green roof, and other main relevant BREEAM or LEED criteria to consider when designing a green roof.

Accreditation Scheme	Biodiversity, Ecology and Land use	Water efficiency & water management	Carbon/energy	Waste	Materials	Acoustic & comfort
BREEAM	***LE 04 Ecological change and enhancement:*** a high quality biodiverse green roof can potentially secure additional credits if it results in overall biodiversity net gain over the project baseline. The green roofs can be designed according to the recommendations of an ecologist. ***LE 05 Long term ecology management and maintenance:*** the management and maintenance requirements of the green roof will be included in the plans implemented for the project.	***Pol 03 Flood and surface water management - surface water run-off***: green or blue roof system can participate to the reduction of stormwater, hence helping to secure additional credits in this category.	***Ene 01 Reduction of energy use and carbon:*** green roofs can help reduce the energy consumption of a building; this may be demonstrated through energy modelling. In addition, a biosolar roof can help further reduce carbon emissions.	***Wst 01 Construction waste management***: consider using waste from demolition if applicable. Reusing aggregates as part of the green roof helps divert waste from landfill. ***Wst 02 Use of recycled and sustainably sourced aggregates:*** aggregates that are used can be obtained from site and within 30km of the site. For example, a brick by product or on-site aggregate can be used as part of the design if not contaminated. ***Wst 05 Adaptation to climate change***: green roofs can be part of a strategy to respond to heat waves. Planting the green roof with drought-resistant species.	***Mat 01 Environmental impacts from construction products - building lifecycle assessment (LCA)***: the green roof can be part of a building LCA options analysis. ***Mat 02 Environmental impacts from construction products – Environmental Product Declarations (EPD):*** some manufacturers of components of green roofs have acquired EPDs which can contribute to credits, including insulation materials, membranes, etc. ***Mat 03 Responsible sourcing of construction products:*** specification of products that have an accreditation from	***Hea 4 Thermal comfort:*** a green roof can contribute to thermal comfort conditions in relation to overheating in summer. However, suitable energy modelling needs to be undertaken to represent this impact. ***Hea 05 Acoustic performance:*** a green roof may contribute to improving the sound insulation performance of the roof. ***Hea 07 Safe and healthy surroundings:*** the green roof may contribute to achieving a credit if it is an accessible outdoor space that can be used by the building users.

				Wst 06 Design for disassembly and adaptability - if two credits targeted, follow design for disassembly guidance in relation to green roof.	approved certification schemes. ***Mat 05 Designing for durability and resilience:*** the 'Guidelines for the Design & Application of Green Roof Systems' (CIBSE, 2013) should be used to make sure that the design is durable.	
LEED	***SS Credit 5.1 Site development – protect or restore habitat:*** green roofs may contribute if the plants are native or adapted and promote biodiversity. Fertilizers, irrigation or regular maintenance should be avoided. ***SS Credit 5.2 Site development – maximize open space:*** green roofs can contribute to the open space requirements.	***WE Credit 1 Water efficient landscaping:*** as part of this credit, the green roof must be designed without irrigation or with drip irrigation or irrigation with reclaimed water. More points available if no potable water is used for landscaping irrigation (except temporarily during landscape establishment) ***SS Credit 6.1 Storm water design – quantity control:*** specify vegetated roofs, pervious paving and other measures to minimize impervious surfaces.	***EA Prerequisite 2 Minimum energy performance & EA Credit 1 – optimize energy performance:*** the use of a green roof may contribute to reduction of energy consumption of the building and improve energy efficiency, therefore contributing to the prerequisite requirement and helping gain points. An appropriate modelling of the green roof performance can be carried out using Energy+	***MR Credit 3 Material reuse:*** recycled or reused materials can be integrated in the design of the green roof to achieve points as part of this criterion. ***MR Credit 4 Recycled content:*** points can be achieved if components like pavers, edge treatments, and growing medium (compost) are from pre-consumer and post-consumer materials.	***MR Credit 5.1 Regional material:*** in order to achieve credits a percentage of the materials must be manufactured and assembled within a 500 mile radius.	***SS Credit 7.2 Heat island effect – roof:*** a green roof should be included for at least 50% of the roof. Alternatively, a green roof in combination with a high albedo can achieve the credit, using the formula: (Area of low albedo roof/0.75) + (Area of green Roof/0.50) ≥ Total Roof Area

Sources: BREEAM New Construction 2018 (BRE Global Ltd, 2019) and LEED – NC (USGBC, 2014)

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