Energy and Buildings 42 (2010) 1582–1591

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Review

Green roofs; building energy savings and the potential for retrofit

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ARTICLE INFO

Article history:
Received 6 April 2010
Accepted 2 May 2010

Keywords:
Green roof
Energy consumption
Structural capacity
Retrofit
Insulation

ABSTRACT

Green roofs are a passive cooling technique that stop incoming solar radiation from reaching the building structure below. Many studies have been conducted over the past 10 years to consider the potential building energy benefits of green roofs and shown that they can offer benefits in winter heating reduction as well as summer cooling.

This paper reviews the current literature and highlights the situations in which the greatest building energy savings can be made. Older buildings with poor existing insulation are deemed to benefit most from a green roof as current building regulations require such high levels of insulation that green roofs are seen to hardly affect annual building energy consumption.

As over half of the existing UK building stock was built before any roof insulation was required, it is older buildings that will benefit most from green roofs. The case for retrofitting existing buildings is therefore reviewed and it is found there is strong potential for green roof retrofit in the UK.

Contents

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0378-7788/$ – see front matter
doi:10.1016/j.enbuild.2010.05.004

1. Introduction

The roof of a building can be fully or part covered with a layer of vegetation known as a green roof. A green roof is a layered system comprising of a waterproofing membrane, growing medium and the vegetation layer itself. Green roofs often also include a root barrier layer, drainage layer and, where the climate necessitates, an irrigation system (not necessary in the UK climate).

A green roof offers a building and its surrounding environment many benefits. These include stormwater management [1,2], improved water run-off quality [3], improved urban air quality [4], extension of roof life [5] and a reduction of the urban heat island effect [6]. Other benefits also include enhanced architectural interest and biodiversity [7].

There are two main classifications of green roofs; extensive and intensive. Extensive green roofs have a thin substrate layer with low level planting, typically sedum or lawn, and can be very lightweight in structure. Intensive green roofs have a deeper substrate layer to allow deeper rooting plants such as shrubs and trees to survive.

Sedum is a common and very suitable plant for using on an extensive green roof. Sedums are succulents, whereby they store water in their leaves, leaving them highly drought resistant. They are small plants that grow across the ground rather than upwards, offering good coverage and roof membrane protection. Sedum is installed in mats, which can be simply rolled onto a roof after the waterproofing and drainage layers have been installed [8]. This means they require minimum maintenance and are easy to install as part of a roof system.

Germany has the largest uptake of green roof technology, where the industry was reported to be worth $77 million in 2008 [9]. Herman (2003) [10] reports that 13.5 km^2 of green roofs exist in Germany, which equates to 14% of all flat roofs. Of these green roofs, 80% are extensive systems, offering the most cost effective solution over intensive types [11]. Extensive roofs are the preferred option for retrofitting onto existing buildings as the structural capacity of the roof will often not have to be increased [2,12]. Livingroofs [13] have undertaken an audit of green roofs in London and are currently aware of 0.93 km^2 covering the Greater London area.

Extensive green roofs are relatively maintenance free and will readily survive in European climates. Williams et al. (2010) [14] however show a poor uptake of green roof technology in Australia. They conclude that more research is needed into substrate material and plant type as sedum matting is unlikely to survive such long periods of hot and dry weather without intensive irrigation.

This paper reviews the current state of knowledge of the potential benefits green roofs offer in relation to building energy consumption. Green roofs greatly reduce the proportion of solar radiation that reaches the roof structure beneath as well as offering additional insulation value. It is identified that older buildings benefit greatest from the additional green roof layer. This leads to a further assessment of the existing building stock and the potential of retrofitting green roofs.

2. Building energy benefits

Buildings account for around half of primary energy consumption, hence CO_2 emissions, in the UK and other developed countries [15]. A large proportion of this energy is used to maintain internal building temperatures through heating and cooling systems. This section of the report will therefore address the potential building energy reduction benefits arising from the enhanced thermal properties of a green roof.

2.1. Reduction of heat flux and solar reflectivity

In summer the exposed area of a black roof can reach 80 °C when the equivalent area beneath a green roof is only 27 °C [16]. Green roofs cool through latent heat loss and improved reflectivity of incident solar radiation. The ratio of total reflected to incident electromagnetic radiation is defined as albedo. Gaffin (2005) [17] suggested that green roofs cool as effectively as the brightest possible white roofs, with an equivalent albedo of 0.7–0.85, compared with the typical 0.1–0.2 of a bitumen/tar/gravel roof [18].

Wong et al. (2003) [19] found from field measurement that in warm conditions the heat in a bare roof accumulated from the day continued to enter the building during the night. Planted roofs suffered less heat gain during the day; hence this effect was much less. By measuring the air temperature at various heights above the green roof it was found that after sunset the ambient air temperature above the vegetation was reduced significantly and continued to cool the ambient air throughout the night. The hard ground however reradiated the stored heat, increasing the ambient air temperature.

Lui and Minor (2005) [20] planted two different green roof systems, each with 75–100 mm of lightweight growing medium in Toronto, Canada. Heat flux transducers were placed below the green roof membranes. A reference roof of the same type (steel deck with thermal insulation above), without greening, was used for a comparison. By measurement they found that the heat gain through the green roof was reduced by an average of 70–90% in the summer and heat loss by 10–30% in the winter. Thermocouples were placed at varying depths throughout the structure, includ-

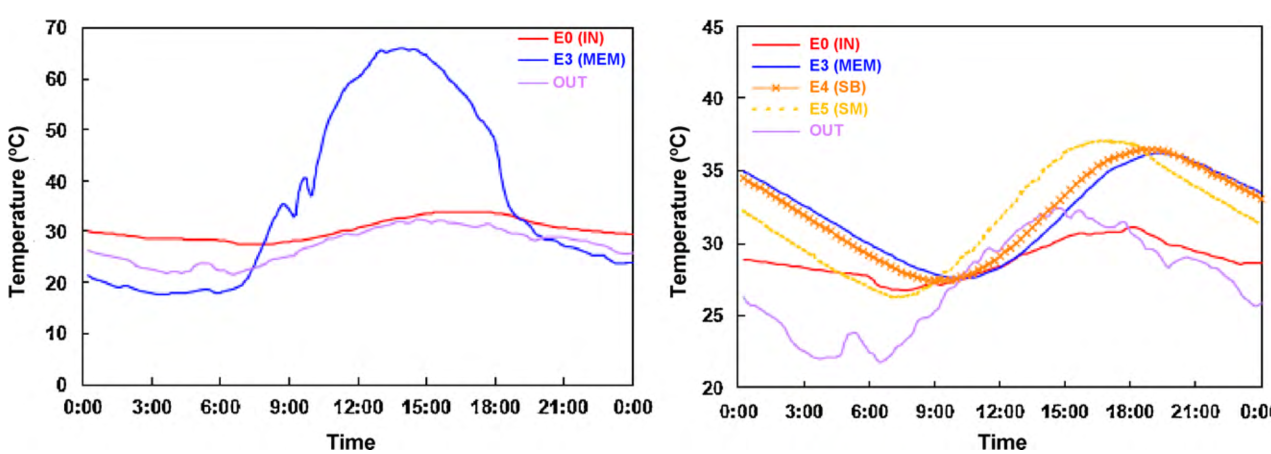

Fig. 1. Summer temperature profiles for a reference roof and green roof respectively.

Source: Lui and Minor (2005) [20].

Table 1
Energy saving potential of green roof on low, moderately and heavily insulated buildings in Athens, Greece, taken from Nichaou et al. (2001) [26].

Roof construction	*U*-Value without green roof (W/m^2 K)	*U*-Value with green roof (W/m^2 K)	Annual energy saving % for heating	Annual energy saving % for cooling	Total annual energy saving
Well insulated	0.26–0.4	0.24–0.34	8–9%	0	2%
Moderately insulated	0.74–0.80	0.55–0.59	13%	0–4%	3–7%
Non insulated	7.76–18.18	1.73–1.99	45–46%	22–45%	31–44%

ing inside the room below. The roof membrane peak temperatures were reduced by the green roofs and delayed from around 2 p.m. to 7 p.m. The temperature profiles comparing the reference roof and typical green roof are shown in Fig. 1. The lines on the graphs represent the temperature recorded by the thermocouples where E0 was placed inside, E3 under the waterproof membrane, E4 under the growing medium, E5 in the middle of the growing medium, and OUT recording the outside temperature.

It can be seen that the internal temperature peak is slightly delayed and the overall temperature is slightly lower than for the reference roof. It appears that the temperature delay is due to the thermal mass effect of the green roof. The substantial layer of insulation present means that only a very small proportion of the large heat flux reduction is translated to a reduction in internal temperature.

In winter the indoor temperature under the green roofs was cooler in the evening and morning than the reference roof, but this was attributed to the different operational needs of the rooms under each roof. The difference in room operating conditions was not mentioned in relation to the summer results. A slightly higher heat loss during the day was found for the reference roof, by 1–2 W/m^2, which shows that the green roofs have reduced heat loss through the roof.

2.2. Thermal mass

The addition of a green roof can improve the insulation properties of a building, hence reduce annual energy consumption. Not only does the roof act to reduce the heat loss from the building in winter and heat gain into the building in summer, it also adds thermal mass to help stabilise internal temperatures year round.

Current UK building regulations require the roof *U*-Value to be 0.25 W/m^2 K for both dwellings and buildings other than dwellings [21,22]. There are, however, notable exemptions from the regulations for industrial type activities. For modern buildings, good insulation levels are mandatory. The problem lies with the existing building stock, where the majority of current buildings were built before such regulations existed. In the UK no insulation requirements existed until 1965, when building regulation set a *U*-Value upper limit of 1.42 W/m^2 K for roofs [23]. This was reduced to 0.6 W/m^2 K in 1976 [24], then further to 0.35 W/m^2 K in 1985 [25]. This means that many UK buildings have much lower insulation levels, if any at all. It can therefore be assumed that the additional insulation of a green roof will result in better energy savings for less well insulated, older buildings. To determine this effect, the thermal conduction properties of the existing roof structure materials and their thicknesses must be known.

Many studies exist that assess the potential energy savings of green roofs when added to buildings, but it should be noted that these are predominantly for warmer climates than the UK. This suggests that green roofs are predominately seen as a passive cooling technique, rather than as a thermal insulator in the winter. Potential winter heating savings have however been investigated [26], although not to the extent of summer cooling. With increasing city temperatures and climate change, summer temperatures of 30 °C assessed here should not be discounted for the UK.

Some of the literature that assesses the energy saving of green roofs does not mention the thermal conductivity of the roof structure, or the thickness of roof materials used [20]. This means that the initial level of roof insulation cannot be estimated. The energy savings found, although often impressive, are therefore case specific and cannot be translated to other buildings.

Santamouris et al (2007) [27], for example, investigated the energy saving potential of green roofs on a nursery school in Greece. They created a thermal model using the thermal simulation program TRNSYS. Each set of experimental data was compared to the model results, with the resultant correlation coefficient found to be 0.92 for the whole set of data. The model was then used to compare the internal temperature distribution of an insulated versus non-insulated building, both with a green roof, compared to one without. They found that the building cooling load was reduced by between 6% and 49%, and the building with the insulated roof had a higher percentage of comfortable internal temperatures. However, scarce mention is given to the roofing materials or their thermal properties. This makes it very difficult to assess the thermal benefit of adding a green roof to buildings with varying roof insulation. The following papers, however, concentrate on the thermal benefits in relation to the *U*-Value of the original roof structure. These give evidence that is applicable to a much wider range of buildings.

The work of Nichaou et al. (2001) [26] is the most relevant here. They determined how a green roof could save energy in buildings with different degrees of existing insulation. They recorded the internal temperatures for two buildings in Athens, both with similar insulation properties but one with a green roof, for three days in July. Without a green roof the internal air temperature exceeded 30 °C for 68% of the period, but with a green roof this was only for 15% of the period. Daily mean, max and min temperatures were found to be 2, 3 and 1 °C lower respectively. Further to this, the thermal simulation program TRNSYS was used to calculate the annual energy requirements for an office building in Athens with varying roof insulation values. The simulation results were initially validated against the collected green roof measurements. Their findings are presented in Table 1.

The model results appear sensible given the different amounts of insulation in each scenario. It can be seen that for well insulated buildings, a very small annual saving is made, but for less well insulated buildings, substantial savings are possible. Here the largest savings are for winter heating, rather than for summer cooling, which differs from the initial impression that green roofs are predominantly seen as a passive cooling technique. This is a useful result given that the greatest UK building energy use in 2009 was for heating, in both the domestic and service sector [28].

Wong et al (2003) [29] conducted field experiments on a roof top in Singapore to record the temperature at various depths of green roofs with differing plants. From the results they calculated the thermal resistance of each plant type using a simple steady-state equation to parameterise a thermal model. They used the DOE-2 simulation program to compare the insulation effects of different plants used for green roofs. They modelled an insulated and non-insulated roof (exposed) roof and estimated the effects of each planting type on each roof. Experimental results were however not used to validate the thermal model.

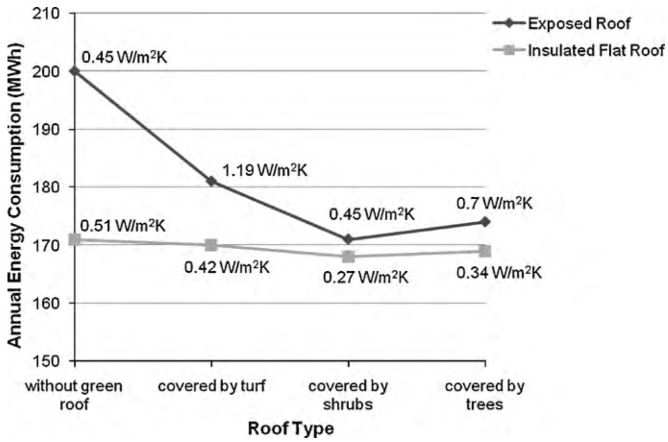

Fig. 2. Comparison of annual energy consumption for different types of roofs on a commercial building. *U*-Values included as data labels.
Data taken from Wong et al. (2003) [29].

The results are shown in Fig. 2. It is interesting to see the improved savings that result from more intensive planting for the non-insulated roof. The turf scenario best represents an extensive roof system. For an insulated roof with a *U*-Value of 0.51 W/m^2 K, a covering of turf reduced the annual energy consumption by only 0.6%. Although the model has not been validated experimentally, this reduction in energy consumption appears plausible given the level of insulation when compared to that found in Table 1. The uninsulated (exposed roof) shows a covering of turf can produce a 10.5% annual energy saving compared with a non-greened, exposed roof. This again shows how the green roof better benefits buildings with poorer roof insulation. The annual energy savings mentioned all come from a reduction in cooling, not heating, but this is perhaps understandable for the climate in question.

Emorfopoulou and Aravantinos (1998) [30] used a stationary mathematical model to calculate the predicted temperature below each material layer for a bare roof and green roof, both with and without thermal insulation. This gave the surface temperatures at the outside and inside of the roof structure. It was found that the absence of an insulation layer widens the gap between summer and winter internal surface temperatures, but is much less extreme on the green roof than the bare. For a planted roof with thermal insulation and *U*-Value 0.4 W/m^2 K, the temperature difference across the roof section does not exceed 2.5 °C, even when external temperatures range from −10 to 40 °C. This agrees with the conclusions drawn from previously mentioned literature, using a calculation method rather than thermal simulation program. They further conclude that although a green roof can improve the thermal protection of a building, it should not replace the insulation layer—an important point that should not be overlooked.

Alcazar and Bass (2005) [31] used the thermal simulation package ESP-r (Environmental Systems Performance—research) to model a multi-story residential building in Madrid, Spain. ESP-r uses the finite element approach to model heat, air, moisture and electrical power flows. The thermal performance was compared for a building without a green roof, with a green roof, and with a green roof capable of water storage, both of which covered the exposed roof surface. Due to the tall nature of the building, the roof only accounts for 16% of the total building envelope. The *U*-Value of the roof was reduced from 0.59 to 0.42 with a green roof and 0.38 for the green roof with water storage. The green roof provided an annual energy saving of 1%, 6% in cooling and 0.5% in heating. The largest reductions were seen in rooms directly below the green roof and no reductions were found more than three floors down. It should be noted that the results were not validated against experimental results.

Table 2
Effect of soil moisture content on Green Roof *U*-Values, data taken from Alcazar and Bass (2005) [31].

Soil	Green roof *U*-Value (W/m^2 K)	Green roof with water storage *U*-Value (W/m^2 K)
0% moisture	0.42	0.38
20% moisture	0.46	0.41
80% moisture	0.53	0.48

When the internal temperature of a building falls below or above a comfortable temperature, heating or cooling is required. In order to assess the amount of heating and cooling used (a large part of building energy consumption), comfort temperatures must be determined. In each investigation reviewed in this paper these temperatures are very similar, and indeed sensible, specified at around 21 °C in winter and 26 °C in summer. In the case of Alcazar and Bass [31], it should be noted that 23 °C was used as the cooling set point. This is lower than the majority of other studies, hence the amount of cooling energy needed to maintain this lower set point will be more significant and predicted savings will appear larger.

Alcazar and Bass [31] further concluded that the shading from solar radiation, evapotranspiration and plant physiological processes affect the roof performance more than the increase in thermal resistance. This is perhaps due to the 20% and 5% energy partitioning initially assumed for evapotranspiration and photosynthesis. Evidence already presented in this paper shows how the presence of a green roof can indeed dramatically reduce the incoming heat flux to the roof structure beneath, but also that the level of insulation of the roof can affect the amount of heat transferred to the room below.

Table 2 shows the effect of soil moisture content on the Green Roof *U*-Values. These improve with drier conditions as expected, because water is a better conductor than air. The soil layer was modelled as 5 cm thick. The total building energy consumption was however not considered to be influenced by the variation in moisture content. This is surprising given the improvement in *U*-Value for dry soil, but given such a small roof area compared to total building envelope, the effect may have been too small to notice.

2.3. Soil thickness and moisture content

Lui and Minor (2005) [20] measured the heat transfer difference between a 100 mm, lighter coloured growing medium compared to a 75 mm deep green roof, compared also to a reference roof with the same structure (steel deck with insulation layer above). The deeper green roof displayed slightly lower heat gain and loss across the measured roofing system. They identified little contribution from the vegetation, indicating that the thermal performance was improved by the thicker substrate.

Del Barrio (1998) [32] used a mathematical model to assess the summer cooling potential of green roofs in Athens, Greece. She found that the thickness of the soil layer, its relative density, along with moisture content, influenced the thermal diffusivity of the soil. As the density decreased from 1500 to 1100 kg m^{-3}, the thermal conductivity of the soil decreased, hence the heat flux through the roof decreased. Additional air pockets in the less dense soil led to an increase in its insulating properties. Conversely, as soil moisture content decreased from 40% to 20%, the heat flux through the roof increased i.e. a wetter green roof is a better insulator. This does not follow the expected result as shown previously in Table 2.

Wong et al. (2003) [29] furthered their investigation described earlier to demonstrate that with every 100 mm increase of soil thickness the thermal resistance of dry clay soil increased by

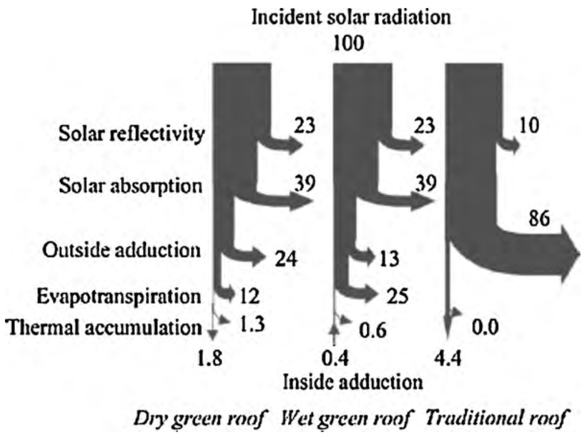

Fig. 3. Comparison of the energetic exchanges of the dry or wet green roof with a traditional roof, summer season.
Source: Lazzarin et al. (2005) [34].

0.4 m^2 K/W. 40% moisture clay soil only increased by 0.063 m^2 K/W. This means that wetter soil is a poor insulator compared to dry. Given once more that air is a better insulator than water, and with supporting evidence in Table 2, this seems a more sensible result.

2.3.1. Evaporative effect and soil moisture content

Feng et al. (2010) [33] used a mathematical model to find that for a typical summer in China, 58% of the heat from a green roof was lost by evapotranspiration, 30.9% long wave radiative exchange, with 1.2% stored or transferred to the room beneath. The model was verified by experimental findings of a comparable situation. It was identified that previous work and thermal simulation programs do not take into account the heat removed by the net photosynthesis effect of the vegetative layer. Their model predicts that 9.5% of the heat was removed by net photosynthesis effects. This was hard to prove from the field measurements and remains subject to the input equations of the model.

Lazzarin et al. (2005) [34] evaluated passive cooling and the role of evapotranspiration with measurements of a Hospital building in North-East Italy for the most dry and most wet periods of the summer season. This experimental data was then used in a finite difference model that calculated the main system fluxes. In the description of the roof make-up, there is no mention of an insulation layer.

Fig. 3 compares the results to show the calculated fluxes for a dry and wet green roof compared to a similarly insulated roof, without greening. It is shown that for a wet green roof there is more than double the heat lost through evapotranspiration than for the dry green roof. The percentage value of evapotranspiration is less than that found by Yufeng, but this could be accounted for by climate variation. The dry green roof reduces the incoming heat flux by 60% with respect to the traditional roof. The additional evapotranspiration of the wet roof means that it not only prevents the heat flux into the building, but acts as a passive cooler, actually removing heat from the building.

2.4. Local temperature effect on air conditioning and PV

Air conditioners cool interior spaces by discharging heat to outside. This process therefore raises the surrounding temperature and even costs of neighbouring air conditioning as HVAC efficiencies depend on input air temperature [35]. The lack of heat build up on a green roof has therefore been suggested to increase the efficiency of air-cooling and ventilation systems [36].

A free cooling system, which can be incorporated into a conventional chiller, can reduce energy consumption when cooling a building. Free cooling can operate when the ambient (outside) temperature falls 1 °C below the cooling fluid returning to the chiller. The cold outside air is then used to further cool this returning fluid, replacing the need for electrical input. Free cooling is particularly effective in the UK where the ambient temperature is below 15 °C for almost 75% of the year [37]. This is most useful for cooling in office buildings in autumn/spring when there are lower external temperatures, but still high internal heat gains from occupants and equipment. It can be deduced that the local cooling effect of a green roof could therefore enable free cooling to operate for a greater proportion of the year, harnessing further energy savings.

Krauter et al. (1999) [38] found that for mono and multi-crystalline photovoltaic panels an increase in local temperature causes a reduction in conversion efficiency of 0.4–0.5% per °C. This is another case where reduced local temperatures of a green roof could enhance the performance of a system. Other authors have also commented on this [39].

Mankiewicz and Simon (2007) [35] retrofitted two buildings in Brooklyn, US with a green roof, PV array and a below grade stormwater capture and recycle system. Condensers were also positioned underneath a green roof and next to vegetated landscape, resulting in cool air conditions with the expectation of increased efficiencies. Results are currently being collected and no data is yet available.

2.5. Green roof energy modelling

Much of the literature already cited has analysed the energy performance of a building with a green roof using models generated by various thermal simulation programs. The results appear to be generated based on the known or measured thermal conductance properties of each roof structure, both with or without a green roof.

Sailor (2008) [40] identified that the existing mathematical models, developed to calculate the energy transfer through green roofs, simplify the effects of evapotranspiration and time-varying soil thermal properties [32,41]. It was further noted that architects and developers need a user-friendly design tool to aid in a numerical assessment of green roof benefits. Sailor therefore generated a green roof energy balance model to be used with the US Department of Energy's building simulation program, EnergyPlus. This now includes Sailor's 'ecoroof' model option, to simulate the effect of a green roof on the modelled building. This enables the user to add a green roof as the outer roof layer on any roof building construction. The model accounts for radiative heat exchange, convective heat transfer, soil heat conductance and storage, and moisture effects. Evapotranspiration from soil and plants is also accounted of in the model. The model has been successfully validated with measurements taken from a green roof in Florida [40]. This is a positive step towards the quantitative assessment of the energy benefits of green roofs, especially for designers when considering inclusion or retrofit of green roofs on buildings.

3. Retrofitting green roofs

Half of the existing 23 million homes in the UK are more than half a century old; and over 80% of the 2025 building stock has already been built [42]. Although a number of buildings in the UK have been retrofitted, or deemed suitable to retrofit with green roofs [43,44], the extent of the potential for retrofit is not yet known. University College London, along with various others, have been working to compile the 'non-domestic building stock database' (NDBS). The database holds information which characterises the existing building stock in four English towns. These are of varying size to best represent the entire country and include Manchester (with a population of 500,000), Swindon (125,000), Tamworth (60,000) and Bury

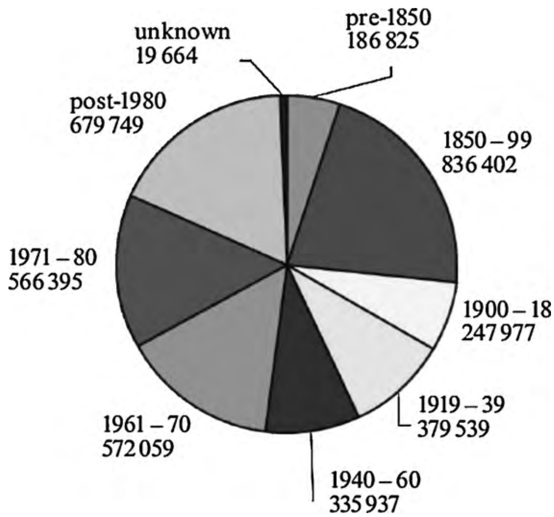

Fig. 4. Breakdown of floor space (m^2) in the four survey areas.
Source: F. Brown et al. (2000) [46].

St Edmunds (30,000) [45]. Fig. 4 shows the age of non-domestic buildings found in the surveyed towns.

This shows that over 50% of existing non domestic buildings were built before 1965, when insulation was not required in building design. As previously established in section 2, a green roof could offer substantial energy savings throughout the year. This means a reduction in carbon dioxide emitted to the environment, as well as a cost to the building owner/occupier.

The current rate of demolition and replacement of the UKs building stock is too low to combat climate change by improving the quality of new developments alone. To make an impact, the wide scale installation of green roofs will therefore have to take place in a way that has a significant impact, hence the majority of green roofs will need to be retrofitted [44].

Fig. 5 indicates just how many buildings were built before 1900 in central Manchester alone, highlighting the extent of existing buildings over a century old in comparison to new.

3.1. Potential for retrofitting

Commercial and institutional buildings are normally repaired/refurbished every 15–20 years and do not require planning permission (unless there is a change of use). This provides a great opportunity for the building owner to green the roof. In a report compiled for Manchester City Council, Drivers Jonas Deloitte [48] state that although retrofitting of green roofs is technically feasible for most commercial or institutional buildings, if strengthening works are required to support the green roof the additional costs would likely outweigh any benefits. However, they add that for most commercial buildings, the additional loads associated with an extensive green roof (typically about 120–150 kg/m^2) do not require any additional strengthening.

Wilkinson and Reed (2009) [49] analysed the potential of retrofitting green roofs to existing buildings in the Central Business District of Melbourne, Australia. The study addresses the large scale potential of retrofitting, not just individual cases. It was concluded that approximately 15% of the building stock was suitable for retrofit. Many opportunities were discounted due to overshadowing of the roof area and unfavorable orientation, but Getter et al. (2009) [50] have shown that various types of sedum can grown in shade conditions. 61% of the buildings surveyed were concrete framed, which are deemed most suitable for retrofitting because minimum structural alterations are required.

Stovin et al. (2007) [2] highlight that the load capacity of the existing roof structure is the predominant constraint when considering a retrofit green roof. Buildings over thirty years old often have more reserve capacity than newer builds due to the improved structural efficiency of modern analysis, design and construction methods. UK medium-rise office buildings with concrete roofs could probably be retrofitted with a green roof with no additional structural modifications. They retrofitted an extensive green roof on an office building in Sheffield to monitor in situ stormwater retention. The green roof was placed on two structural roof types: a reinforced concrete slab and profiled steel decking surfaced with plywood, without additional structural modifications in both cases. The concrete slab had an estimated capacity of 8–10 kN/m^2, enough to support a substrate depth up to 800 mm. This shows a strong case for retrofitting this building type in the UK (Fig. 6).

Lambeth is one of the most densely populated inner London boroughs [8]. The Ethelred Estate has recently been regenerated to provide a better environment, added value and sense of well being for its community whilst educating others in environmental issues. As part of the refurbishment, an extensive green roof system, from manufacturer Bauder, was added to over 4000 m^2 of flat roof tops, making Ethelred the largest green roof retrofit case in the UK (Fig. 7).

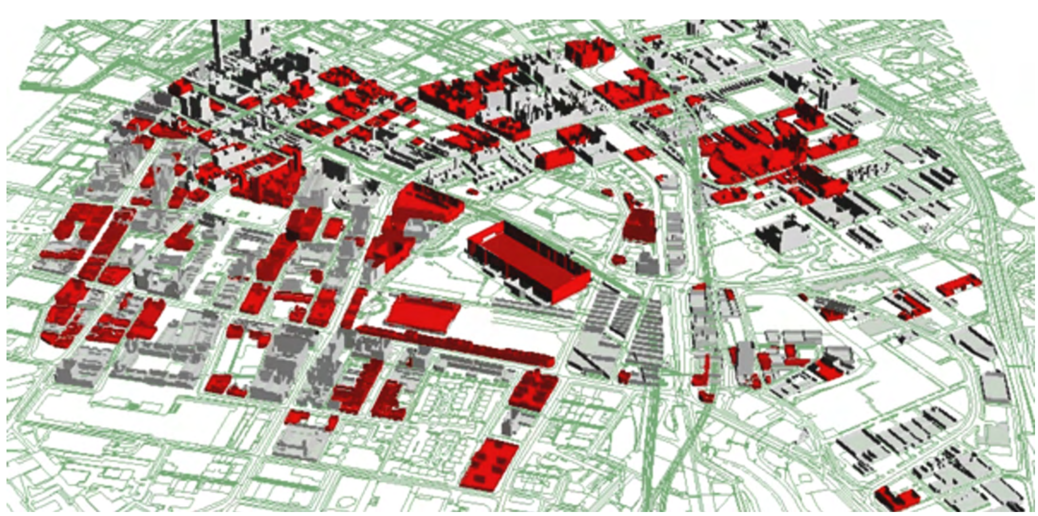

Fig. 5. 3D image of Central Manchester showing buildings built before 1900 highlighted.
Source: The Bartlett School of Graduate Studies website [47].

Fig. 6. Trial beds on the Ryokka Project building laid on a) a concrete slab roof, and b) a steel framed roof.
Source: Stovin et al. (2007) [2].

Despite the higher initial cost of the green roof when compared to a more traditional option, innovation was encouraged by the £5.3 m GOL (Government Office for London) grant obtained. The importance of whole-life cost, together with 'investment' in resident satisfaction was deemed important by the social landlords. The thermal benefits were also taken into account, helping to address winter fuel poverty [51].

3.1.1. Costs

The Green Roof Centre [52] estimate that an extensive green roof system costs between £60 and £100/m^2, dependent on specification and many variants; such as new build or retrofit. Various case studies for retrofitting a number of public buildings in Manchester produced by consultants Drivers Jonas Deloitte [48], were estimated at a supply and installed cost of £65/m^2. These are both however generic and initial estimates, therefore likely to be low.

Alumasc – one of the UK's main green roof suppliers – suggest that costs could range from £50/m^2 up to £150/m^2 [53] depending on whether the old roof needed to be stripped back and re-waterproofed or whether the existing roof was in sufficiently good condition to simply overlay.

Data from Lambeth council, which is based on real green roof retrofit experience, suggests costs of between £120 and £180/m^2. The Ethelred estate, Kennington, Bauder extensive system (4000 m^2) constructed in 2005, cost £716,000 equating to £179/m^2. Portland Grove, another refurbishment in the Lambeth area has 961 m^2 of sedum roof which cost £94,673 along with an additional cost for scaffolding of £20,300. This equates to a total cost of £120/m^2. Lambeth Council estimated that it would add 13% (based on 60 year whole-life costs) to incorporate green roofs compared to non-green roof [54]. A reasonable estimate to retrofit extensive green roof would appear to be around £150/m^2 (at 2010 prices).

In terms of whole-life cost analysis, Carter and Keeler (2008) [55] calculated the Net Present Value (NPV) of a green roof to be 10–14% more expensive than a conventional roof over a 60 year lifetime. They identified that if energy costs increase or green roof construction costs decrease or stormwater prevention becomes a higher public priority, then green roofs will become more economically attractive. They also noted that the positive social benefits of planting green roofs should not be overlooked and provide additional incentive to the decision process.

Kosareo and Ries (2006) [56] performed a comparative environmental life cycle assessment of green roof for a 1115 m^2 retail store in Pittsburgh, US. They compared an intensive green roof, an extensive green roof and a conventional ballasted roof. The increased

Fig. 7. Original flat roofs at Ethelred Estate and green sedum roofs after refurbishment.
Source: Photograph courtesy of Jon Lissimore, Lambeth Council.

roof lifetime of 45 years compared to the control roof lifetime of 15 years, along with the thermal conductivity of the growing medium were found to have a significant impact on the life cycle analysis. It was concluded that although initial costs were high, the energy and cost savings made over the building lifetime meant that the green roof was an environmentally preferable choice. This is a more favorable outcome toward the green roof than found by Carter and Keeler and highlights that the outcome of the life-cycle assessment of a green roof depends on the assumptions made for the calculations involved.

3.2. Structural implications and allowances

As it is very difficult to obtain structural as-built drawings for existing buildings, even more so for those over 10–15 years old [43], a structural survey is recommended in the majority of cases in order to determine a building's roof load bearing capacity before designing the retrofit of a green roof. The weight of the green roof system must first be considered when determining the potential to retrofit.

3.2.1. System weight

Munby (2005) [43] identifies the lightest sedum system fully saturated at 0.546 kN/m^2, offered by manufacturer Bauder [57]. Wark and Wark (2003) [58] state total wet extensive green roof loads can range from less than 49 kg/m^2 to approximately 98 kg/m^2. This equates to approximately 0.5–0.96 kN/m^2.

3.2.2. Reserve structural capacity as a result of code changes

Across Europe new structural design standards (Eurocodes) have been introduced and changes to the loading code [59] suggest that existing structures might have the necessary reserve capacity to accommodate the additional loading of a green roof.

The design value of a combination of actions on a roof is given in BS-EN-1991 [59] by the expression:

$$\sum_{j\geq 1}\gamma_{G,j}G_{k,j} + \gamma_{Q,1}Q_{k,1} + \sum_{i\geq 1}\gamma_{Q,i}\psi_{0,i}Q_{k,i} \qquad (1)$$

where G_k is the 'dead' or permanent load, and Q_k is the main 'live' or variable load. These loads are both multiplied by the partial factor, γ. Any other variable actions are multiplied by the partial factor, and also a combination factor, ψ.

Clause 3.3.2(1) of BS EN 1991-1-1 states that "On roofs, imposed loads, and snow loads or wind actions should not be applied together simultaneously."

Design to limit state British Standards has used partial safety factors for loading of 1.4 for dead and 1.6 for imposed. The corresponding values in Eurocode based design are 1.35 for permanent (dead) actions and 1.5 for variable (imposed) actions. For UK design, the resistance of structural members remains essentially unchanged, thus a reduction in the partial safety factors for loads results in a slight increase in reserve capacity. A more detailed consideration of the loading combinations in Eurocode 1, in particular the use of factors for combinations of loading (ψ) and the reduction factor (ξ), may justify further reserve capacity in existing designs.

Where roofs have previously been built for plant loading there is further scope for green roof retrofit, potentially with a thicker soil layer.

As an international example of spare structural capacity, Munby (2005) [43] identified a reduction in snow load design for roofs in Ontario, Canada from 1.95 to 1.07 kN/m^2. This leaves 0.88 kN/m^2 spare design capacity.

Fig. 8. Rooftop with protective chippings.
Source: Driver Jonas Deloitte/Gary Grant 2009 [44].

3.2.3. Spare structural capacity—ballast

There are three main types of existing roof construction to be considered when retrofitting a green roof. These are described as follows:

A *cold roof* is a traditional roof design which many of the older building stock will have. Insulation is laid below the main roof structure, with an air gap to prevent condensation between the insulation and roof slab. Asphalt can be applied as a waterproofing layer on flat roofs, but needs protecting from UV rays and is traditionally covered with chippings. Single ply (plastic) membranes are also used and must be covered by pebbles, gravel or paving to add ballast.

A *warm roof* has insulation placed above the roof slab, reducing the risk of condensation inside the building. Asphalt, single ply or felt is then applied on top of the insulation for waterproofing. Modern felt does not need protection from UV.

The waterproofing layer can alternatively be placed below the insulation; this is an *inverted warm roof*. The insulation must now be held down, typically by pebbles or paving slabs. The waterproof layer is subsequently protected very well. Fig. 8 shows a protected roof.

Where ballast is used on a roof, particularly an inverted warm roof, the roof is likely to be capable of supporting an extensive green roof in place of the ballast [43]. Paving slabs weigh approximately 160–220 kg/m^2 (1.6–2.2 kN/m^2), and gravel 90–150 kg/m^2 (0.9–1.5 kN/m^2) [60], which in each case could be replaced with an extensive green roof with a decent thickness of substrate.

Additional insulation can be also be added to the green roof build up for older buildings constructed when insulation was not required to meet building regulations.

4. Energy saving for retrofit

Wilkinson and Reed (2009) [49] found that around 15% of buildings in the Melbourne Central Business District were suitable for green roof retrofit when they carried out an assessment of the cities buildings. According to Herman (2003) [10], 14% of all flat roofs were greened in Germany in 2003.

Data for annual energy consumption in the UK is available from the Department of Energy and Climate Change. Fig. 9 shows the final energy consumption in the service sector by sub-sector and end use for 2007. Using the most recent data available (2007) for the UK service sector, it is possible to estimate the potential annual energy savings that retrofitting green roofs could provide.

For example; commercial offices, educational, government and healthcare buildings together used 139 PJ of energy for heating in

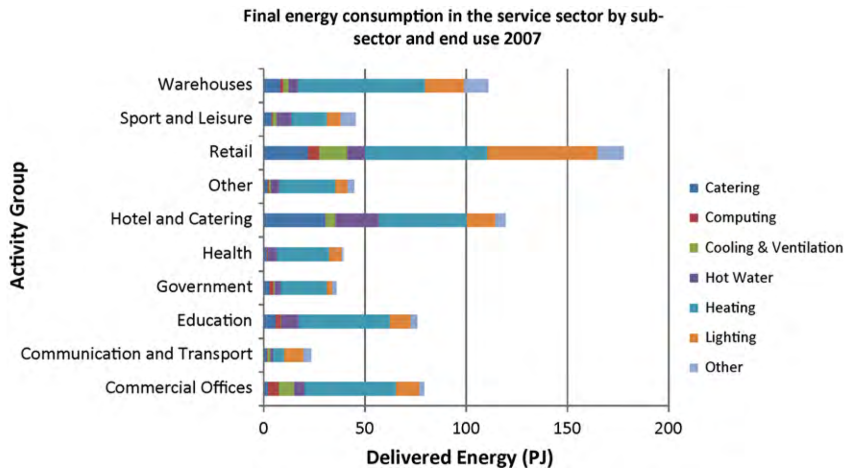

Fig. 9. UK service sector final energy consumption 2007.
Data taken from the Department for Energy and Climate Change [28].

2007. It can be seen in Fig. 9 that the energy used for cooling and ventilation in these buildings is very small in comparison to that used for heating.

From Fig. 4 it can be seen that over half of the existing building stock was built before 1965, with a further quarter built between 1965 and 1976. It has previously been identified in Section 2.2 that before 1965 there was no requirement to have insulation in buildings, and between 1965 and 1976 the building regulations defined a maximum roof insulation U-Value of 1.42 W/m^2 K.

Table 1 summarises potential energy savings for heating as 45% for non-insulated buildings and 13% in moderately insulated buildings. By applying these savings to 50% and 25% of the existing building stock respectively, and assuming that 15% of these buildings could realistically be retrofitted with green roofs, an estimated annual saving of 5.37 PJ could be achieved.

5. Conclusions

There are many different reported benefits that the addition of a green roof to a building can offer. One of these benefits is the potential for building energy savings where a green roof can reduce annual heating and cooling loads. Many studies have been conducted to assess the extent of energy savings possible with extensive green roofs. Several of these studies however lack definitive information regarding roof structure thermal properties. This means that the results, although often very positive in terms of saved energy, are only applicable to the situation in question. The investigations which give roof U-Values with and without the green roof, along with information on material build up and thickness, generate results which can be applied to the assessment of future design situations.

An extensive review of the existing literature has exposed the following key factors when assessing their energy saving potential in the context of building use:

1. Green roofs can significantly reduce energy use in buildings with poor insulation values, both in summer cooling and winter heating.
2. Modern buildings, built to the 2006 UK building regulations will have much higher U-Values associated with better roof insulation so green roofs will save no, if very little, energy.
3. The thicker the soil substrate on the roof, the better it reduces heat gain/loss into/out of the building.
4. A less dense soil has more air pockets and is hence a better insulator.
5. The moisture content of the soil affects the extent of heat lost through evapotranspiration. In cases of wet soil, heat has been shown to be drawn out of a building where evapotranspiration effects are high. The conductivity of the soil also increases with moisture content, meaning dryer soil conditions offer better thermal insulation.

Older buildings are generally less well insulated, if at all, so will see more energy savings with the addition of a green roof than new buildings. Due to such a slow annual building turnover rate, to make a difference in building energy use and combating climate change, existing buildings could be retrofitted with green roofs.

For this to happen, the existing roof must be able to support the weight of the green roof. Retrofitting is a realistic option for widespread application given changes in building design codes, meaning that older buildings, when reassessed to the latest design codes, are likely to have inherent spare structural capacity largely as a result of a slight reduction in the load factors applied to permanent and variable actions. There are many inspirational green roof retrofit cases for existing buildings in the UK and beyond where no modifications have been required to retrofit a green roof, bringing many benefits beyond energy saving and environmental education to the community.

Thermal simulation modelling has often been used to predict the heating and cooling load savings of a building with a green roof. Several different programs have been used for the studies assessed in this paper. The ecoroof option developed for EnergyPlus by Sailor however allows the user to apply a green roof as the outer layer of the roof structure and takes into account conductive, radiative, convective and moisture effects, giving accurate results when compared to real life situations. This will allow designers to accurately model the energy benefits of green roofs, especially in evaluating the benefits of retrofitting green roofs onto specific existing buildings.

Acknowledgements

This research was funded by the Engineering and Physical Sciences Research Council (EPSRC) and conducted as part of the E Futures DTC at Sheffield University.

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