BUILDING INTEGRATED VEGETATION AS AN ENERGY CONSERVATION MEASURE APPLIED TO NON-DOMESTIC BUILDING TYPOLOGY IN THE UK

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ABSTRACT

Amongst a large range of passive energy conservation measures (ECMs), building integrated vegetation (BIV systems) is witnessing a rapid growth in both research and market development (Bass and Baskaran, 2003). Unfortunately, their uptake remains limited in the UK, although the existing non-domestic building stock is in urgent need of energy conservation in order to meet the UK’s carbon reduction target.

This research aims at analysing the performance of BIV systems as an ECM specifically to the non-domestic building typology. For a six-storey office building in London, a sensitivity analysis is conducted using different parameters to assess the performance of BIV systems. The optimised solution of these parameters that achieve maximum energy savings was applied to the building typology. The outcomes of this paper can be used as a design tool for BIV systems in order to maximise energy savings of a building.

INTRODUCTION

Urbanisation typically replaces planted groundcover with the rooftops of buildings (e.g. concrete). This has led to a rapid degradation of green open spaces. In a year, 0.4ha/1 acre of trees in a city park absorb the same amount of carbon dioxide as that produced by 41850 km/26,000 miles of car driving (Rusell et al., 2007). What if these parks are fragmented and transferred to these defunct rooftops, or even the building facades? Most of the unused space in towns and cities is on the rooftops: for example, buildings (and therefore roofs) cover 24,000 hectares or 16% of Greater London (GLA, 2002). One obvious way to reclaim that lost green space is to integrate vegetation with the building elements.

Building integrated vegetation systems (BIV) consists of green roofs, vertical greening systems on both exterior facades and interior walls. The term ‘green’ is synonymous with ‘living’, ‘breathing’ and ‘vegetated’ in this context. BIV systems have a range of benefits. Green roofs can mitigate the urban heat island effect, improve the energy efficiency of buildings, reduce storm water runoff, increase biodiversity, purify water and air as well as elongate the life span of roofs. Because of the benefits mentioned above, green roofs have become a focus of current research (Feng et al., 2010). Green walls fulfil all of the above benefits on a much larger scale of application since the exterior wall area of a building is more than the roof area.

In this study, the performance of BIV systems as an ECM was the criterion for assessment. All other performance indicators of BIV systems are beyond the scope of this research.

There is an estimated 200 million m² of roof area in the UK, which could potentially be converted to green roofs, in some cases requiring modification to the roof structure. These roofs are flat roofs on offices, schools, hospitals and other public buildings, as well as blocks of flats (CIBSE, 2007). Hence, for initial analysis, a typology of a six-storey deep plan office building in London is chosen from a joint study between UK Green Building Council and University College London (UKGBC, 2007).

RESEARCH AIM

The overall aim of the project was to formulate key parameters that influence the design of BIV systems specifically for non-domestic buildings and analyse the effect of these systems on the microclimate of the indoor environment and the consequent energy consumption of the building.

METHODOLOGY

1. The UKGBC study on the energy consumption of non-domestic buildings constructed a stock model for non-domestic buildings in the UK. Since the typologies held a degree of statistical representation, a deep plan office typology (Figure 1) was selected for initial analysis. The construction type and thermal properties of the building fabric are given in Table 1. EnergyPlus uses various sources for gathering climate files. The climate file for London (GBR_London.Gatwick.037760_IWEC.epw) is taken from IWE weather data source (ASHRAE, 2001).

1 The International weather for Energy calculations (IWE) data files are ‘typical’ weather files suitable for use with building energy simulation programs for 227 locations outside the USA and Canada. The files are derived from up to 18 years of DATSAV3 hourly weather data originally archived at the U.S. National Climatic Data Center.
2. Key vegetation-dependent and building-dependent parameters were formulated for sensitivity analysis:
   For green roofs:
   i. Vegetation dependent parameters included:
      – Vegetation coverage area (Leaf Area Index)
      – Growing media depth
   Various other vegetation dependent parameters like plant canopy density, plant height, stomatal conductance (ability to transpire moisture), roughness factor and soil moisture conditions (including irrigation and precipitation) were not be considered for the main analysis, after initial sensitivity investigations revealed them to be insignificant for this case study compared with the two chosen key parameters.
   ii. Building dependent parameters included:
      – Internal comfort temperatures set by occupants
      – Roof deck insulation
   For green walls:
   i. Building dependent parameters included:
      – Orientation of wall
      – Internal comfort temperatures set by occupants
      – Roof deck insulation
   The vegetation dependent parameters were not considered for the analysis of green walls. Instead, the optimized solution for vegetation parameters (vegetation coverage area) in the green roof analysis are applied and assumed constant. The substrate depth is assumed constant as per general manufacturer’s details.

3. An optimum solution in terms of energy efficiency for all types of BIV systems was derived and applied to the non-domestic building typology. Energy modeling in EnergyPlus was carried out to determine the effect of BIV systems on the indoor air temperature and the energy consumption of the building.

SIMULATION RESULTS AND DISCUSSION

Sensitivity analysis of green roofs

An un-shaded block-model of dimensions 30m*30m*3.7m, the top floor of the typology, was considered for analysis with highly insulated walls, airtight construction, but with an un-insulated roof for the base-case scenario. A vegetation layer was then applied to the roof surface.

Vegetation coverage area

Leaf area index or vegetation coverage area for plant cover can range from 0.002 (sparse) to 5 (highly dense). Both of these extreme values were modelled and the results compared. For direct comparison with limited variables, the substrate depth was kept constant at 150mm.

Effect on internal air temperatures

On the peak summer day, the HVAC system was taken to be non-operational and therefore does not affect internal air temperatures. A large temperature variation can be seen for the base case (Figure 2) with the lowest value at 28°C (08:30) and the highest at 38°C (18:30). This range obviously moves outside of the assumed thermal comfort zone (18°C -24°C). When the green roof was applied, both LAI models showed a similar trend with minimal variation in indoor air temperature. However, for the LAI 5 model, the temperature curve lies within the range of...
C, which is much closer to the comfort level than for the base case scenario. Using the green roof with LAI 5 can reduce the average internal air temperature by 8°C compared with the base case.

On peak winter day the minimum outside dry-bulb temperature reaches -5.9°C (Figure 3). The HVAC system was non-operational on this day. It can be seen from Figure 3 that the temperature difference between the LAI variants is not significant. At 12:30 hrs, for example, the internal temperature for LAI 0.002 is 4.7°C whereas for LAI 5 it is 5.6°C, however for the base case it is -0.4°C.

Hence for the same substrate depth, a lower LAI would have a slight effect on the heating loads, but increasing LAI in summer would almost double the energy savings. This would work well for deciduous vegetation where the LAI automatically reduces in winter due to shedding of leaves.

The annual loads for both LAI models against the base case scenario are given in Table 3.

Summary of findings of LAI sensitivity analysis

<table>
<thead>
<tr>
<th>GREEN ROOF (150mm substrate depth)</th>
<th>PERIOD</th>
<th>LOWER LAI (0.002)</th>
<th>HIGHER LAI (5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saving in Energy consumption</td>
<td>Annual</td>
<td>13.5%</td>
<td>15%</td>
</tr>
<tr>
<td>Saving in Heating load</td>
<td></td>
<td>15%</td>
<td>16%</td>
</tr>
<tr>
<td>Saving in Cooling load</td>
<td></td>
<td>3.2%</td>
<td>7%</td>
</tr>
<tr>
<td>Average internal air temperatures</td>
<td>Peak summer</td>
<td>Same as base case</td>
<td>Reduces by 6.5°C</td>
</tr>
<tr>
<td></td>
<td>Peak winter</td>
<td>Increases by 4.2°C</td>
<td>Increases by 4.9°C</td>
</tr>
</tbody>
</table>

Growing media (substrate) depth:

Even though a higher LAI (with 150mm) works satisfactorily as an ECM for the annual period, the substrate depth plays an influencing parameter as it changes the thermal conductance of the roof layer. Four models achieved by LAI 0.002 and LAI 5 with 60mm and 450mm substrate depth are analysed against base-case.

Effect on internal air temperatures

During the peak summer day (Figure 4), it can be seen that when the base case achieves a temperature peak of 38.4°C the green roof with 450mm depth and LAI 5 can reduce the indoor air temperature by 11.6°C. A higher LAI provides the most energy saving when coupled with higher substrate depth. During the peak winter day (Figure 5), and irrespective of the LAI used, a 450mm substrate depth increases the indoor air temperature by up to 7.4°C, compared with the base case, as shown by Figure 5. A higher LAI performs slightly better in this case.

<table>
<thead>
<tr>
<th>Annual loads of LAI models against base-case</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASE CASE</td>
</tr>
<tr>
<td>Cooling load (kWh)</td>
</tr>
<tr>
<td>Peak summer week</td>
</tr>
<tr>
<td>Peak winter week</td>
</tr>
<tr>
<td>Annual</td>
</tr>
<tr>
<td>Total energy consumption</td>
</tr>
</tbody>
</table>
The internal comfort temperatures set by the occupants play an important role in terms of energy conservation and influence the performance of green roofs as an ECM. As per the annual climatic data of London, the comfort zone for occupants stretches from 18°C (heating set-point) to 24°C (cooling set-point). The internal comfort temperatures were hypothetically increased from 24 °C to determine the effects on cooling loads during summer, and decreased from 18 °C to determine the effect on heating loads during winter.

The cooling loads reduce rapidly in both the base case and green roof models with the increase in set-point temperatures (Figure 6). At 24 °C set-point temperature the base case shows a cooling load of 280 KWh and the green roof reduces this load still further to 259 KWh. Beyond 24 °C, with every increase in cooling set-point temperature there is a gradual decrease in loads as would be expected. At 26 °C (upper extent of comfort zone), the base case shows a cooling load of 77 KWh and the green roof reduces this to 29 KWh. After this set-point a degree rise in set-point temperature gives a gradual decrease in cooling when ultimately, at 28 °C, the building with a green roof becomes free running as the cooling loads become 0 KWh. At this temperature the base case shows a cooling load of 13 KWh. For every 1 °C reduction in set-point temperature the cooling loads in the peak summer week reduce by 67 KWh (0.1%) on average for the base case scenario and by 65 KWh (0.1%) on average for the green roof scenario.

By decreasing the heating set-points in both base case and green roof models a rapid decrease in heating loads is seen as well (Figure 7). The base case and green roof models a rapid decrease in heating loads during winter.

**Table 4**

Summary of findings of growing media depth and LAI sensitivity analysis

<table>
<thead>
<tr>
<th>PERIOD</th>
<th>GREEN ROOF LAI 5</th>
<th>GREEN ROOF LAI 0.002</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SUBSTRATE DEPTH (60MM)</td>
<td>SUBSTRATE DEPTH (450 MM)</td>
</tr>
<tr>
<td>Savings in Energy consumption</td>
<td>13%</td>
<td>19.5%</td>
</tr>
<tr>
<td>Savings in heating load</td>
<td>13.8%</td>
<td>21.2%</td>
</tr>
<tr>
<td>Savings in cooling load</td>
<td>7%</td>
<td>5%</td>
</tr>
<tr>
<td>Average internal temperatures</td>
<td>Peak Summer</td>
<td>Decreases by 6.3 °C</td>
</tr>
<tr>
<td></td>
<td>Peak winter</td>
<td>Increases by 4.5 °C</td>
</tr>
</tbody>
</table>
case at a set-point of 22 °C shows a heating load of 7163 KWh. At the other extent of the comfort zone (set-point 18 °C) the loads reduce to 4470 KWh. The green roof at 22 °C reduces the heating load to 5345 KWh as against the base case. At the other extent of the comfort zone (set-point 18 °C) the loads reduce to 3224 KWh when the green roof is applied.

For every 2 °C reduction in set-point temperature the heating loads in the peak winter week reduce by 1000 KWh (1.3%) on average for the base case scenario and by 950 KWh (1.6%) on average for green roof scenario.

The performance of the green roof as an ECM for the annual period decreases as the insulation thickness increases (Figure 8). For insulation thickness above 400mm (Expanded polystyrene (EPS)), the effect of the green roof on the energy consumption of the building appears to become negligible.

Also the trend in reduction of annual energy consumption against increasing insulation thickness shows that every base case (insulated roof) can be replaced by an equivalent green roof construction producing the same annual energy consumption. Designers would find this trend useful for obtaining other benefits of green roof (increasing bio-diversity, reducing storm-water run-off, etc., lesser embodied energy) against synthetic insulation. In this case the green roof would not be behaving as an ECM. A green roof can act as an effective ECM if applied to un-insulated or insulated roofs [with a restriction to insulation thickness < 400mm (for EPS)].

**Sensitivity analysis of green walls**

Energy calculations for green walls are dependent upon variables including wall orientation, sun angle, wind flow, and microclimate around the building (Cantor, 2008).

From the green roof analysis it was found that a green roof with denser vegetation coverage (LAI 5) and deeper substrate depth achieved the greatest reduction in annual energy consumption against a base case scenario. Modular living walls (Figure 9) consist of polypropylene modules (280mm X 280mm) with a depth of 90mm. The substrate depth was considered to be 90mm so that the structural loading on the building wall remains minimal without compromising on the requirement of the plants. In the analysis the vegetation cover was taken as LAI 5. For green walls the additional building dependent parameters for sensitivity analysis would be:

- Orientation of wall
- Internal comfort (set-point) temperatures set by the occupants
- Insulation in wall

<table>
<thead>
<tr>
<th>Green roof with LAI 5, and 450mm substrate depth</th>
<th>Period</th>
<th>Internal comfort temperature 24°C-cooling 22°C-heating</th>
<th>Internal comfort temperature 24°C-cooling 18°C-heating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Savings in energy consumption</td>
<td>Annual</td>
<td>19.5%</td>
<td>-26.7%</td>
</tr>
</tbody>
</table>

Since the earlier sensitivity models of green roof were analysed with 18 °C heating and 22 ºC cooling, by raising the cooling setpoint by 2 ºC raises the annual energy savings by 7.2% (Table 5).

**Insulation in roof:**

Another building dependent parameter that has an effect on the performance of green roofs is the synthetic roof insulation. Green roofs have an insulating property due to the thermal characteristics of the substrate. Green roofs should replace the need for synthetic insulation as both serve the same purpose. Hence a sensitivity analysis of the effect of varying insulation thickness on the performance of green roofs as an ECM has been conducted.
The heat gains/losses through the wall depend upon its orientation to the sun. A sensitivity analysis was conducted by applying vegetation on each facade, or all four facades at once to derive the optimum solution for green wall energy saving performance.

For the base case scenario, highly insulated roof and windows and un-insulated cavity walls were considered in order to encourage heat exchange through the walls only and to optimise the performance of green walls. Internal comfort temperatures were set as 24 °C cooling and 22 °C heating and low air leakage construction (0.05ach⁻¹).

Effect on annual energy consumption
By vegetating all of the facades of the building, a 3.35% annual energy saving can be achieved (Table 6). When a singular façade of any orientation is vegetated a marginal saving of 0.7-0.9% can be achieved in annual energy consumption.

A singular green façade increases annual cooling load as per orientation. The increase in cooling loads is a contradictory finding because a green roof (60mm substrate depth and LAI 5) would cause a 7% reduction in annual cooling load. An east, north, west and south vegetated façade causes a cooling load increase of 1.4%, 2%, 1.4% and 1.5%, respectively. If all of the facades are vegetated, the annual cooling load increases by 6.6%.

The reason behind the increase of cooling load could be the air-tightness of the envelope, and lack of natural ventilation. Since the building is extremely airtight (0.05ach⁻¹) and there is limited natural ventilation, the built-up of heat inside the space due to internal gains cannot be easily dissipated to the outside in summer. The vegetated facade increases the thermal resistance of the fabric (lower U-value), further reducing heat loss through the fabric from the inside. This results in overheating of the space, hence placing additional load on the cooling system. Different natural ventilation strategies, with varying air-change rates, would affect the performance of the green walls against the base case. This is further explained in the work of Wong et.al. (2009) where the simulations of office buildings in Singapore found a reduction of 10.35% in cooling loads, using natural ventilation and should form the basis of future research in this field.

However, the air-tightness of the building achieves minimum heat loss (through ventilation), thus reducing the annual heating loads by 5%. Also a singular green facade of any orientation can achieve a 1.3% saving in annual heating load. Hence a different ventilation strategies would need to be designed according to the seasonal performance of green walls.

Comfort(set-point) temperatures:
The heating set-point, which was originally taken as 22 °C, was further decreased by 4 °C to analyse the effect on the annual energy consumption.

Table 7
Energy saving for green walls for different set-point temperatures

<table>
<thead>
<tr>
<th>Savings in annual energy (%)</th>
<th>All walls</th>
<th>North</th>
<th>East</th>
<th>West</th>
<th>South</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating 22°C</td>
<td>3.35</td>
<td>0.89</td>
<td>0.87</td>
<td>0.86</td>
<td>0.70</td>
</tr>
<tr>
<td>Heating 18°C</td>
<td>3.48</td>
<td>0.92</td>
<td>0.99</td>
<td>0.98</td>
<td>0.68</td>
</tr>
</tbody>
</table>

Efficiency scale

Table 6
Summary of findings for energy savings of green walls in orientation analysis

<table>
<thead>
<tr>
<th>GREEN WALL WITH LAI 5 90MM SUBSTRATE DEPTH</th>
<th>PERIOD</th>
<th>EAST FACING</th>
<th>NORTH FACING</th>
<th>WEST FACING</th>
<th>SOUTH FACING</th>
<th>ALL WALLS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Savings in Energy consumption</td>
<td>Annual</td>
<td>0.9%</td>
<td>0.9%</td>
<td>0.9%</td>
<td>0.7%</td>
<td>3.35%</td>
</tr>
<tr>
<td>Savings in heating load</td>
<td></td>
<td>1.3%</td>
<td>1.3%</td>
<td>1.3%</td>
<td>1.1%</td>
<td>5%</td>
</tr>
<tr>
<td>Savings in cooling load</td>
<td></td>
<td>None. Increases by 1.4%</td>
<td>None. Increases by 2%</td>
<td>None. Increases by 1.4%</td>
<td>None. Increases by 1.5%</td>
<td>None. Increases by 6.6%</td>
</tr>
</tbody>
</table>
It can be seen that when heating is set to 22 °C the annual energy savings when all facades are vegetated is 3.35 % (Table 7), increasing further to 3.48% when the heating is set to 18 °C. Hence, lowering the heating set-point temperatures increases the efficiency of green walls by a marginal amount. Each green wall of every orientation performs differently for different set-point temperatures. For example, when considering heating at 22 °C the north vegetated wall is most efficient, and when considering heating at 18 °C the east vegetated wall is most efficient. Therefore the performance of the green wall as per orientation is dependent on the season (outside temperatures) and internal comfort temperatures set by the occupants (thermostat set-point temperatures) for a certain set of parameters including ventilation rate, air infiltration, occupancy, HVAC system and their respective operational schedules.

### Insulation in wall:

![Figure 10 Effect of varying insulation thickness of wall on annual energy consumption](image)

The effect of insulation on the performance of a green wall is similar to that of a green roof. The performance of the green wall as an ECM for the annual period decreases as the insulation thickness increases. Also, as for green roofs, every base case (insulated wall) can be replaced by an equivalent green wall construction producing the same annual energy consumption. For example, (see Figure 10) for an annual consumption of 54025 KWh, a base case wall (brick, cavity filled insulation thickness 25mm) can be replaced by a green wall (vegetation on brick un-insulated cavity wall) producing a similar annual load (53952 KWh). For EPS insulation thickness beyond 400mm, the green wall has no effect on the annual energy consumption against the base case wall.

### CONCLUSION

The energy saving potential of BIV systems is determined by the two key parameters of vegetation coverage area (leaf area index) and substrate depth. The effect of these parameters on efficiency is dependent on seasonal climatic variation. A lower LAI with higher substrate depth would work most efficiently in winter, whereas a higher LAI with lower substrate depth would work most efficiently in summer (Table 8). However, higher leaf area index and substrate depth increases the annual efficiency of the green roofs as an ECM.

As the analysis suggests, the energy saving potential of green walls seems to be dependent on building parameters such as building fabric (thermal conductance), construction quality (air-tightness), internal comfort temperatures set by occupants and seasonal ventilation strategies. A high airtightness construction that would minimise ventilation heat loss from the building would increase the efficiency of the BIV system in winter; however, it would also cause a detrimental effect on the cooling loads of the building in summer when a green wall system is used.

The efficiency of BIV system can be increased significantly by modelling the building parameters appropriately as per the climate of the site location.

### Table 8

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Substrate depth</th>
<th>Vegetation coverage area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>150mm</td>
<td>0.002</td>
</tr>
<tr>
<td></td>
<td>450mm</td>
<td>3.000</td>
</tr>
<tr>
<td></td>
<td>5.000</td>
<td>5.000</td>
</tr>
</tbody>
</table>

**LIMITATIONS OF SIMULATION TOOL**

EnergyPlus version V5 as an energy simulation engine has been extremely beneficial in the performance analysis of BIV systems due to its green roof model. However the green roof model has certain limitations such as:

1. 0.002<=LAI<=5; Hence vegetation coverage higher than LAI value 5 cannot be modelled.
2. 50mm <=substrate depth<=500mm ; Intensive roofs with substrate depths higher than 500mm and extensive roofs with substrate depth lower than 50mm cannot be modelled.
3. EnergyPlus version V5 is incapable of modelling soil-less BIV systems, such as the hydroponic green wall systems. A material layer (substrate) of minimum 50mm is required for the green roof model; whereas the hydroponic vegetated wall consists of felt saturated with nutrient water (max.
thickness = 20mm) as ‘substrate’. Hence the later versions of the software need to be updated as per the latest BIV technologies in the market.

4. Only one building element can be taken as vegetated for building simulation. Green roof and green wall cannot be modelled simultaneously.

REFERENCES


