2022-01

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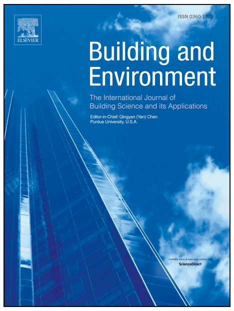
http://hdl.handle.net/10026.1/18258

10.1016/j.buildenv.2021.108491
Building and Environment
Elsevier



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PII: S0360-1323(21)00887-8

DOI: https://doi.org/10.1016/j.buildenv.2021.108491

Reference: BAE 108491

To appear in: *Building and Environment*

Received Date: 19 July 2021

Revised Date: 19 October 2021

Accepted Date: 24 October 2021

Please cite this article as: Fox M, Morewood J, Murphy T, Lunt P, Goodhew S, Living wall systems for improved thermal performance of existing buildings, *Building and Environment* (2021), doi: https://doi.org/10.1016/j.buildenv.2021.108491.

# Title Page

## Title

# Living wall systems for improved thermal performance of existing buildings.

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## Highlights

- Green and living facades can improve the thermal performance of existing buildings.
- There is a lack of empirical data on effects of living wall to building insulation.
- Findings demonstrate a 31% improvement to traditional masonry wall U-values.

## Abstract

Living wall systems are a relatively new form of façade cladding treatment on buildings. Bringing a host of benefits such as added biodiversity, they also have the potential to aid the thermal efficiency of a wall construction by offering an extra layer of thermal resistance. Yet few studies have been conducted to ascertain the thermal influence of living wall systems can have on existing buildings.

This study reviews the impact of living walls upon the thermal and environmental performance of buildings and isolates a lack of research that directly measures associated retrofitted living wall thermal performance. A case study then monitors the heat flux through a pre 1970s uninsulated cavity masonry wall construction that has been retrofitted with an external living wall system face. Results are compared with an identical wall build-up on the same elevation without the living wall cladding.

Results found that the calculated thermal transmission value for the pre 1970s wall with an additional Living wall façade cladding was 31.4% lower than that of the same wall without the living wall. Furthermore, diurnal fluctuations in heat flux were lower over the study period for the wall with the living wall system cladding. These findings demonstrate that a living wall façade offers a viable solution for helping to minimise heat loss from existing buildings of this construction.

## Keywords

U-value, Living wall systems, Green walls, Heat flux, Insulation, Energy Conservation, Sustainable Buildings, Space Heating, Cladding.

## Abbreviations

Green Façade (GF), Living wall systems (LWS), Root mean square (RMS).
U-value presented in watts per meters squared, Kelvin (W/m$^2$K)

**Word count:** 6326

## Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

## 1. Introduction

In Britain, buildings directly account for 17% of UK Greenhouse Gas Emissions (85 $MtCO_2e$ in 2019) [1], and space heating accounts for over 60% of all energy used in buildings [2]. Whilst modern policy and construction methods strive to minimise energy use, it is acknowledged that there is a correlation between the age of buildings and increased energy in use [3], with older buildings being the largest contributors to carbon emissions.

Within England, approximately 57% all domestic [4] and non-domestic [5] buildings were built before 1964. Many other existing conurbations across the globe have similar rates of pre-existing buildings and therefore are likely to have associated thermal standards within their existing building fabric. Therefore if the UK is to reach its target of net zero carbon emission by 2050 [6, 7], and other global targets it will be critical to address the energy use of existing building stock.

One of the most common forms of construction in the UK, some parts of Europe, North America and Asia since the 1920s are masonry walls, with cavity systems accounting for around 70% of UK dwellings [8]. The thermal performance of this form of construction is relatively poor, with measured thermal transmission values in the region of 1.3 to 1.1W/$m^2$K [9] and 1.56W/$m^2$K [10] for masonry cavity walls built before 1990. This date is significant, since the England and Wales building regulations changed in 1990 to lower the thermal transmission value with nominal U-values for external walls falling from 1.0W/$m^2$K in 1976 to 0.45W/$m^2$K in 1990 [11]. This led to increased use of cavity fill insulation to meet the regulations. To date there are around 5.3 million UK properties (30% of the total building stock) that do not have cavity insulation, many of which are perceived as being hard to treat* [8]. *(Hard to treat infers associated difficulties in installing either cavity, internal or external wall insulation to lower the wall's thermal transmission value).

Strategies to improve the thermal performance of existing walls includes the use of cavity fill, internal or external wall insulation [12]. Each method has unique practical benefits and limitations. The unique features often alter the time related response of walls, leading to specific thermal performance characteristics that can not only reduce heat loss but result in more comfortable interior spaces in extended periods of high external temperatures [13, 14]

Whilst insulation will reduce wall heat loss, it is estimated that wind driven convection can increase heat loss from building surfaces by 50% [15]. This issue is recognised by Anderson [16] and BS EN 6946 [17], who estimate that exposed walls with a surface resistance of 0.04$m^2$K/W can be improved to between 0.1$m^2$K/W and 0.13$m^2$K/W (for high emissivity surfaces) if using some form of external ventilated cladding / rain screen protecting the exposed surface. This could include the incorporation of a container system used to provide the growing medium for housing plants close to an existing wall.

Yet there is great complexity in estimating the flow of heat through a ventilated cavity due to a range of factors such as conduction within still air, convection from air movement and radiation from the inner cavity surface. Sanders [18] suggest that the estimated U-value for a traditional timber framed wall with a ventilated cavity to its cladding could vary by between 3% and 7% dependent on the emissivity of the materials used and the degree of ventilation. Whilst much work has been undertaken to consider the complexities of cavity resistances, Davies [19] comments on the limited work that has been undertaken to verify the assumptions made for thermal resistances of ventilated cladding cavities.

There are many options available for external claddings on buildings, however a relatively new form of external wall covering are 'green walls'. These green walls also known as 'vertical greening systems' are typically categorised into Green Façade (GF) and living wall systems (LWS). Whilst GF use plants directed to grow from a single point (usually at ground level) up a trellis or framework, LWS differ by growing plants from multiple pockets of soil and other medium across the entire area of the façade [20].

The aim of this paper is to investigate the potential for an external LWS to improve the fabric U-value of existing cavity walls. This shall be investigated through these objectives:

1. Review existing academic literature on GF and LWS.
2. Investigate the change in fabric U-value to an existing uninsulated masonry cavity wall example case study when retrofitted with an external LWS façade cladding treatment.

## 2. Theory

Green wall systems offer a wide range of unique benefits [21] that more traditional inert façade claddings such as timber or cementitious materials cannot provide. Benefits include enhanced sound absorption [22], pollution mitigation and improvement in air quality [23], increased biodiversity [24], added value from biodiversity [25], and psychological improvements from perceived organic aesthetic [26, 27].

In the context of more traditional cladding / rain screens offering some improvement in surface resistance, several studies have been conducted to explore the benefits that green walls can have on the thermal behaviour of buildings.

One area of previous research has focused on the reduction in the urban heat island effect in warm climates, where foliage from such façades minimises the direct solar exposure on more traditional thermally massive construction materials such as masonry [28],lowering the risk from re-emitted thermal radiation to the urban realm. By minimising the solar gains on buildings, green walls have also been found to lower the indoor air temperature of buildings in warm climates through foliage offering shading to the façade [21]. Ottele et al., [15] explain how solar energy is used by the vegetation, with 5-30% being reflected, 5-20% used for photosynthesis, 10-50% turned into heat and 5-30% transmitted through the leaf. They also add that 20-40% of the solar exposure is used for evapotranspiration, which is the process of drawing heat through evaporated moisture from the leaf [21]. The net result is that the ventilated air gap between the green wall and the adjoining construction is cooled by the foliage restricting the path of solar energy to the building. This is supported by Di & Wang [29] who found that peak cooling loads could be reduced by 28% for west facing ivy covered walls when exposed to direct sunlight. Adding to this, Wong et al., [30] found that wall surface temperatures could be reduced by over 11°C when using a vertical greenery system. Work by Safikhani & Baharvand [31] explored the effect of increasing the ventilated cavity on lowering wall surface temperatures, and found that a 30cm cavity on western located walls provided the most optimal solution when utilising a green wall for cooling. Also work by Cameron et al., [32] has explored the effect that different forms of foliage have on cooling.

Plant geometry varies according to the growth form with the majority of living wall plants consisting of evergreen, perennial, herbaceous species. This reflects the requirement for dense, low growing plants with attractive foliage all year round [33]. Dense foliage growth in evergreen perennials is most often associated with plants with meristems (growth points) occurring at ground level and typically have tussock forming or clumped growth forms. In addition to being aesthetically pleasing, dense foliage of clump forming grasses, ferns and flowering plants have the added ecosystem services of sequestering relatively large amounts of carbon in their foliage, plant tissues, and as soil organic carbon [34]. As well as wall cover and shade this dense plant biomass may provide additional thermal insulation for buildings [35]. Tangjuank [36] found that the thermal insulation of particleboards produced from pineapple leaves, which has a similar clumped growth form to a living wall staple, Luzula spp. was 0.035 W/m.K with density of 210 kg/m3, which was closed to the commercial insulator.

In addition to work undertaken on the cooling effects that can be gained from green walls, there is some research into the insulative benefits that such a system can bring. There is evidence that an external layer of foliage can lower the rate of heat loss from a building, particularly as it minimises wind driven convective cooling by providing a buffer to wind [21]. Work by Eumorfopoulou & Kontoleon [37] discuss the buffering of wind, suggesting that foliage creates pockets of still air amongst the leaves, which reduce the heat transfer coefficient. The effect of this though is dependent on the density of the foliage. Indeed, evidence from a green wall study in UK winter conditions suggests the variation between recorded green façade energy saving of 21% and 37% compared to bare walls was explained by plant establishment and foliage factors [38]. Cameron et al., [38] suggests energy savings with this system could be as high as 40 – 50% in UK winter settings during periods of extreme weather (strong rain and wind, cold). Further research by Yoshimi [39] show how a green wall can provide an insulating effect by helping the external wall behind the green wall to maintaining a higher and more stabilised surface temperature when compared with surface temperatures of an external wall without a green wall. It is not just the external wall surface temperature that is reduced, the air in the gap between the foliage and the wall is also warmer due to the buffering effect of the leaves. Riley [33] indicates a 38% cost reduction in winter energy use resulting from the installation of green walls

The insulating effect of foliage is found to be greater at night, when larger variations in air temperature might be expected. This factor is supported by Nan et al. [40], who found LWS provide an insulating effect during the evening and early morning. Riley [33] also reports that the greatest benefits can be gained from green walls at the times of lowest and highest temperatures of the heating and cooling season. By protecting the exposed wall during the coldest times of the day, there is some levelling of diurnal wall temperatures, which will minimise heat flow through a structure. Additional findings from Nan et al. [40] found that soil temperatures were greater than air temperatures and that LWS helped to raise internal temperatures by between 0.4°C and 1.7°C compared with walls without greenery. However, in winter the soil in the pockets of LWS is likely to be wetter than summer, which Charoenkit & Yiemwattana [41] argue could lead to greater heat loss in winter due to increased evaporative cooling. Dependent on the plant species, there is also an issue related to the shedding of foliage in winter. Such loss of foliage might lower the insulating effect suggested by others, though could lead to benefits from added solar exposure of the wall behind [42].

If the more biologically orientated research linked to green and living walls is assessed, it is clear that much can be learnt from natural systems where there is empirical data on how plant geometry and leaf morphology is a determining factor for thermal performance in plants [43]. At present there is limited work applying knowledge from natural habitats to options for different plant types in living wall systems [38].

Leigh et al., [44] has shown that leaf morphology and anatomy has a significant influence on leaf surface thermal dynamics. Smaller leaves with increasing leaf dissection (pinnate or bipinnate) were found to have higher levels of heat dissipation [44] and reduce water loss [45]. Smaller, thicker more dissected leaves can be an advantage to plants growing on water stressed vertical surfaces of buildings but provide lower levels of shading from solar radiation [44]. Larger leaves provide higher levels of shade [46] and could be important in minimizing excessively high heat loads on building surfaces. Rupp and Gruber [43] model heat transfer for different leaf shapes and found that shape-driven transfer enhancements were higher for models with small leaves with finely toothed edges, with local cooling up to 10 °C below air temperature. Leaf surface is also important, increased leaf surface pubescence (hair cover) and leaf margin complexity increase boundary layer thickness, reducing leaf surface heating [43]. Pubescence and lighter-coloured leaves reflect more light providing added leaf surface cooling and water conservation [45, 47]. When assessing all of these variables Bau-Show Lin & Yann-Jou Lin [46] found that foliage density followed by leaf thickness, leaf texture, and leaf colour had the greatest contribution to surface-soil cooling. Further work on living wall systems is required to test these factors. There were some aspects that the review did not provide definite answers to, such as the impact the type of organic matter has on thermal performance. Similarly investigating the effect that irrigation has on soil and conductivity, whether different plant species offer varied improvements in performance and exploring the effect that annual growth has on overall performance. In some instances, this empirical data can be used to model/simulate the possible building performance outcomes associated with different plant/layout/substrate and existing walling options.

Many studies have focused on modelling [48, 49], simulation [42, 50-54],multi-layer temperatures [30, 37, 55] and humidity [40] monitoring; however, few have used in-situ heat flux to assess thermal conductivity through LWS. Of those who have used heat flux methodologies, Mazzali et al., [56] have investigated the rate of heat flux through foliage to the masonry wall behind. This was to assess the cooling properties of a LWS. In another study, Manso & Gomes [57] investigated a cork-based LWS attached to an insulated metal building in Portugal. Over three 14-day periods, they utilised temperature and heat flux monitoring. Results were promising and found that minimum internal surface temperatures could be increased by 7°C during winter periods with the addition of the cork based LWS. Additional work using heat flux investigations on LWS in a winter period was conducted by Tudiwer & Korjenic [58]. In this study, two types of living wall were investigated and compared with un-covered sections of wall. Results found that the LWS monitored gave between 0.13m$^2$K/W and 0.68m$^2$K/W improvement in thermal resistance over non-greened walls. These findings are also promising and suggest that further work on different types of LWS is needed to better understand the winter period improvements that can be made by installing these systems to an existing building.

Despite previous work in this field, there remains a lack of research investigating the thermal performance improvement that could be made to a traditional masonry cavity wall. In the UK, this is significant, given the large number of existing masonry cavity walls present. Whilst traditional strategies for improving the thermal resistance of such walls might have added insulation, literature suggests that LWS could offer an alternative solution for thermal improvement, whilst also providing other unique benefits such as biodiversity, aesthetic and air quality improvements. Furthermore, understanding the scale of the thermal improvement offered in this setting will help define the sustainability potential of this approach given the potentially high environmental lifecycle and overall energy burden this system may exert [15].

Due to the limited research on thermal performance improvement from LWS on masonry cavity walls, a practical development from this theory was deemed necessary.

The following sections present an investigation into the thermal performance of an externally applied LWS façade cladding treatment placed over an existing uninsulated masonry cavity wall. The setting for this is Plymouth, UK, which is sited in a maritime climate. The objective will be to compare two identical sections of existing walling (one covered with the living wall) using heat flux sensors to determine whether any improvement can be made with the selected living wall system.

## 3. Material and Methods

### 3.1 The case study building

The building investigated under this study is a relatively small two storey detached office located on the University of Plymouth campus. The original building was constructed as a timber workshop in the

18th Century and has since been extended over the years to convert into an office building. Reflecting this historic development, the construction comprises of a variety of materials, though the external walls were a mixture of rendered solid stone and uninsulated rendered brick / block (Masonry) cavity walling.

In 2019 this building received extensive internal and external renovation. Whilst this regime of improvements did not include additional insulation to the external walls, one major intervention was the installation of an externally planted living wall.

The living wall used for this building is the modular ‘Fytotextile’ system, which was supplied by Scotscape [59]. This flexible felt fabric sheet system is made up of waterproof synthetic layer, absorbent moisture layer (middle layer) and porous outer felt layer and makes use of these to form pockets for soil and planting. The tested LWS uses a mixture of evergreen plant types including sedges (*Carex spp)*, ferns (e.g. *Dryoteris spp)*, rushes (e.g. *Luzula spp)* and flowering shrubs (e.g. *Sarcocca confusa*). Plants were installed with a standard multi-purpose potting compost. These fytotextile sheets are fixed to the wall via a frame and plants are watered using a tubular drip-irrigation system from above the sheets. Figure 1 shows a photograph of the system used in this study.

*Figure 1. Photo of the Fytotextile living wall system.*

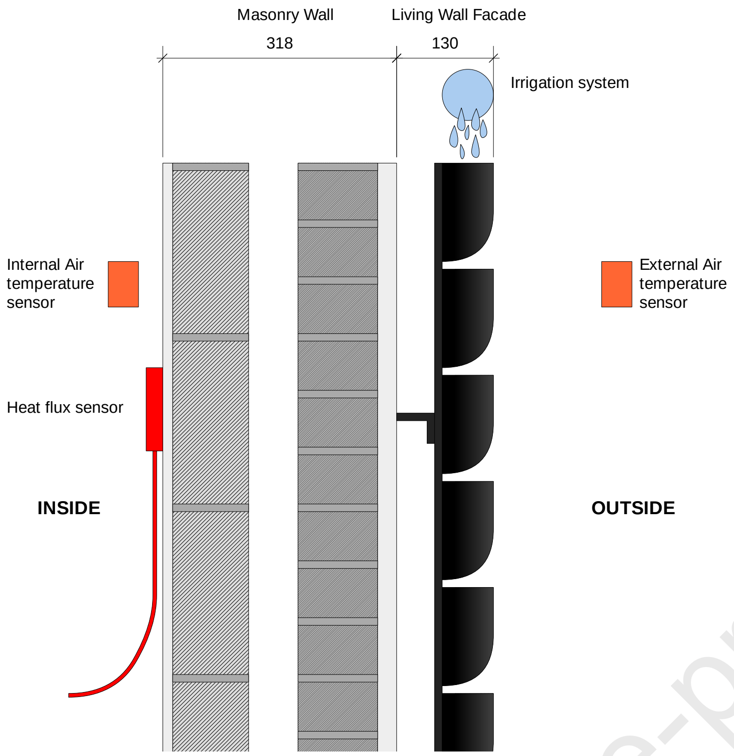

*Figure 2. Cross section through the wall showing diagrammatic location of sensors.*

The living wall was installed on the west and south elevations to the building. These elevations were selected for their ease of retrofit and comprised of masonry cavity wall construction. Figure 2 presents a section through the cavity wall, showing the attachment of the Fytotextile living wall system. Figure 3 shows a photo of the case study building, which illustrates the extent of the living wall system.

*Figure 3. Photo of case study building, showing locations of monitoring setup.*

To verify the inner wall construction of the masonry cavity wall, an invasive inspection was carried out using a borescope inserted into a small drill hole in the wall. It was deemed through the identification of the constituent materials that the masonry wall was constructed before the 1970s.

Illustrated in figure 2, the existing wall comprised of an inner leaf of dense concrete block (125mm) and an outer leaf of brick (105mm). These layers were separated by a 50mm uninsulated cavity. The internal face of the wall was finished with a gypsum plaster (13mm). The external face of the wall was finished with a painted render finish (25mm). The render had a rough cast finish. The exact physical properties of these materials were not known due to the limited access for destructive investigation, however it is possible to estimate the theoretical U-value, calculated from data provided by CIBSE [60]. Using a medium density concrete block at 0.77W/mK and external leaf brick at 0.84W/mK, with a cementitious render (1.13W/mK) and gypsum plaster (0.18W/mK), a predicted U-value for the wall could be calculated to be 1.37W/m$^2$K.

## 3.2 Monitoring methodology

To investigate the difference in thermal transmission between an existing cavity wall covered with an outer layer of living wall vegetation and one without, two sets of heat flux sensors were installed to monitor the thermal conductivity of the two wall locations:

- Location 1. Uninsulated masonry wall.
- Location 2. Uninsulated masonry wall with external living wall façade.

Figure 4 shows a plan of the building, indicating the locations of the monitoring setup locations and the living wall locations.

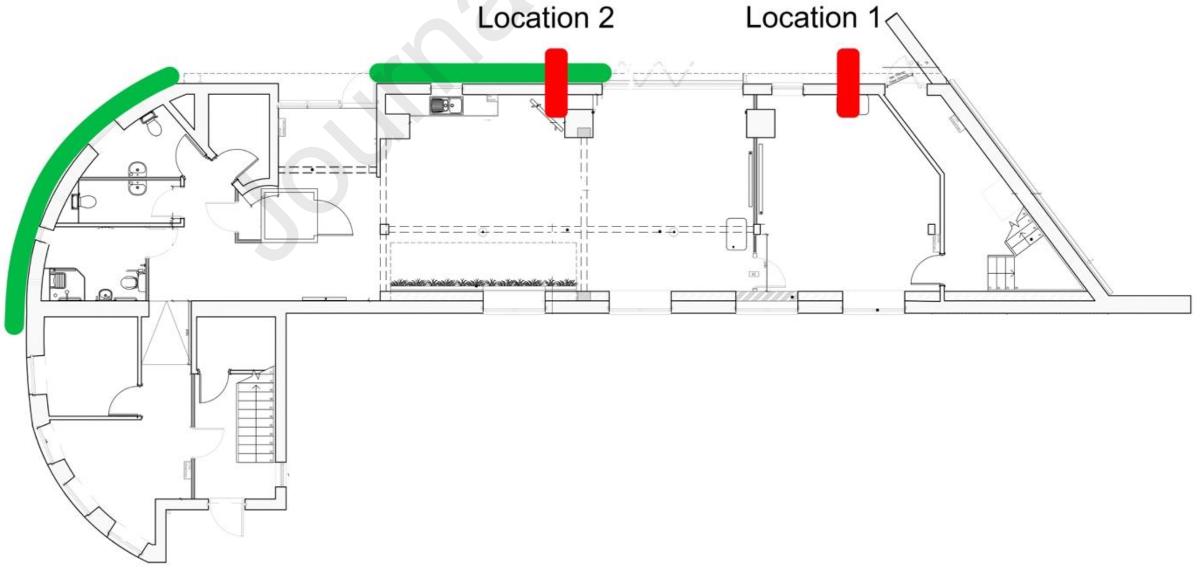

*Figure 4. Building plan showing location of monitoring locations (red) and extent of living walling (Green).*

It is important to note that these two locations were in separate room zones. For each zone, the air temperature was monitored. The results from each zone would be used in part to calculate the in-situ U-value for the wall. As illustrated in figure 4, the design of the case study meant that it was not possible to monitor the two different wall states in the same space.

There are several methods for measuring and calculating the in-situ U-value of an existing building construction. Hukseflux [61] outline a method of monitoring a construction build-up using internally wall mounted heat flux sensors alongside thermocouples, which attached to the internal and external surfaces of the construction. A variation to this method is presented by the Building Research Establishment (BRE) [62], who utilise a similar method derived from BS ISO 9869-1:2014, which is known as the 'average method' [63]. Within the average method, surface temperatures are replaced with measurements of internal and external air temperatures. The average method of in-situ U-value calculation is discussed by others in relation to monitoring existing wall constructions [64-67]. For the case study in this paper, the average method of in-situ U-value measurement was chosen.

Monitoring was undertaken from 18:00 on 7th November 2019 to 18:00 on 12th December 2019. This five-week period was selected due to its forecast of seasonally cool external temperatures, and with knowledge that the internal heating system would be on throughout the investigation period.

For this experiment two sets of calibrated HFP01 HFM sensors were used for these experiments [61]. A T620bx thermal camera [68] was used to help determine the most appropriate location for measurement [63], which avoided thermal bridges and known defects. Sensors were also placed away from room corners and window jambs to minimise the effects of thermal bridging [64]. All sensors were positioned at equal heights from floor level and equal horizontal distances from masonry wall ends to limit the variability of the masonry walling between the two measurement locations. This would also help to minimise the variability in external climatic conditions and their effect on the two wall locations. For example, wind driven convection, precipitation and solar radiation.

For each of the two setups, two heat flux sensors were taped to the internal face of the wall to be measured using a heat sink compound applied between the sensor and wall. An average reading was calculated between the two sensors and used in later analysis.

Each set of heat flux sensors were connected to a calibrated Campbell Scientific CR1000 data logger [69], which were used to collect data for the experimental period. At the end of the experiment, the data was downloaded and analysed to determine the in-situ U-value.

To aid comparison between the two data sets, sensors were placed on the same external wall, less than 10m apart and faced the same orientation, therefore being exposed to the same climatic conditions.

The methodology for the heat flux experiment was developed in accordance with ISO 9869-1:2014 [63], and previous work by Asdrubali *et al.* [70] and Baker [9, 64]. For the monitoring period a 15-minute temporal resolution for data collection was selected. All the apparatus was coordinated so that measurements were recorded at the same time. In selecting the duration of the experimental period, Biddulph *et al.* [71] recommend a three week data collection period, while Baker [64] recommends monitoring for 27 days. Because the building being inspected would be in constant use during the experiment, it was decided that a five-week data collection period would be used.

For the internal and external air temperatures four Hobo MX1101 data loggers [72] were used. Each wall state had a pair of data loggers, where one was located on the outside close to the monitoring location and the other was located inside close to the heat flux sensor setup. The data from these was validated by further collecting air temperature data using a wireless weather station, which was used to monitor external climatic conditions prior to and during the experimental period.

### 3.3 Analysis equation

Data from all sources of apparatus was downloaded at the end of the monitoring period and collated in excel where it was reviewed to calculate the moving average thermal transmission for each section of walling. [61-63]. The equation used was taken from the BRE average method for in-situ U-value calculation [62]:

$$U = \frac{Q}{T_i - T_e} = \frac{Q}{\triangle T}$$

*Equation 1. In-situ U-value equation [62]*

In order to evaluate the thermal transmission over time, this equation can be modified to take account of consecutive data in a moving average equation:

$$U_t = \frac{\sum Qi}{\sum (T_i - T_e)i} = \frac{\sum Qi}{\sum \triangle Ti}$$

*Equation 2. Moving average in-situ U-value equation [64].*

Where:
$U_t$ = Average U-value over *t* hours (W/m$^2$K)
ΣQi = Heat flux at interval of *i* hours (W/m$^2$)
ΣΔTi = Temperature difference between internal and external space at interval of *i* hours (K)

## 4. Results

### 4.1 Monitoring results

Data from each of the monitoring tools was collected at the end of the five-week study period.

Internal air temperature results presented a pattern that clearly showed when the space heating turned on and off during a daily cycle. Weekends were distinguishable due to the absence of space heating during this two-day period. The average internal air temperature for this study period was 17.2°C (±4.2°C fluctuations). External air temperatures varied from between 5°C and 12°C during the study period, with a high of 15°C and low of 1.5°C. The average external air temperature was 8.9°C (±6.8°C fluctuations).

*The 15-minute spaced data interval was calculated using U-value* Equation 1 as a first step to analysis. The results from this are presented in Figure 5.

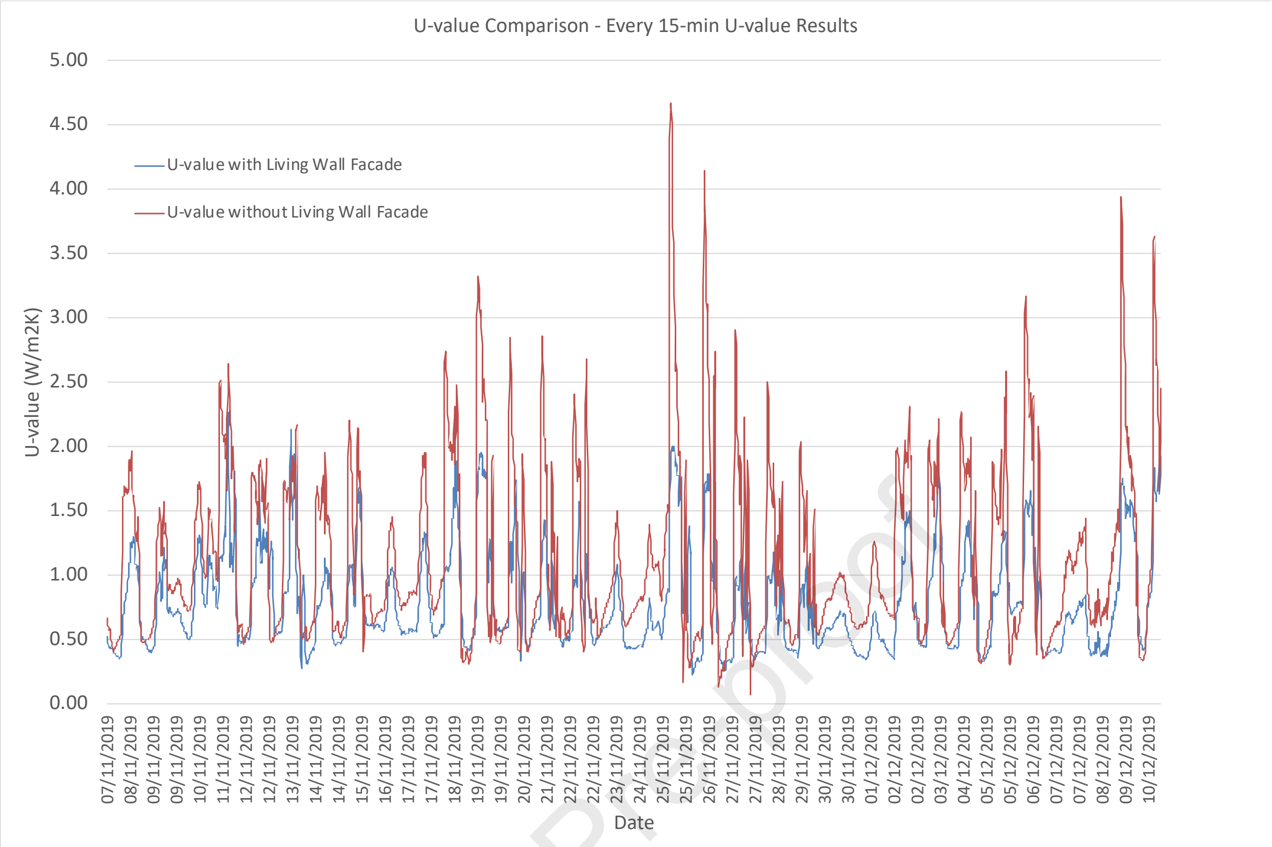

*Figure 5. 15-minute data interval U-value results for 5-week study period.*

Uninsulated masonry wall without living façade

- Highest measured U-value: 4.67W/m$^2$K
- Lowest measured U-value: 0.07W/m$^2$K
- Spread between values: 4.60W/m$^2$K

Uninsulated masonry wall with living façade

- Highest measured U-value: 2.26W/m$^2$K
- Lowest measured U-value: 0.22W/m$^2$K
- Spread between values: 2.05W/m$^2$K

Figure 6 takes a five-day period from Monday 25th to Friday 29th November and focuses in more detail to observe the fluctuations of each wall state over a shorter period. This shows the difference in measurement fluctuations between the two wall states.

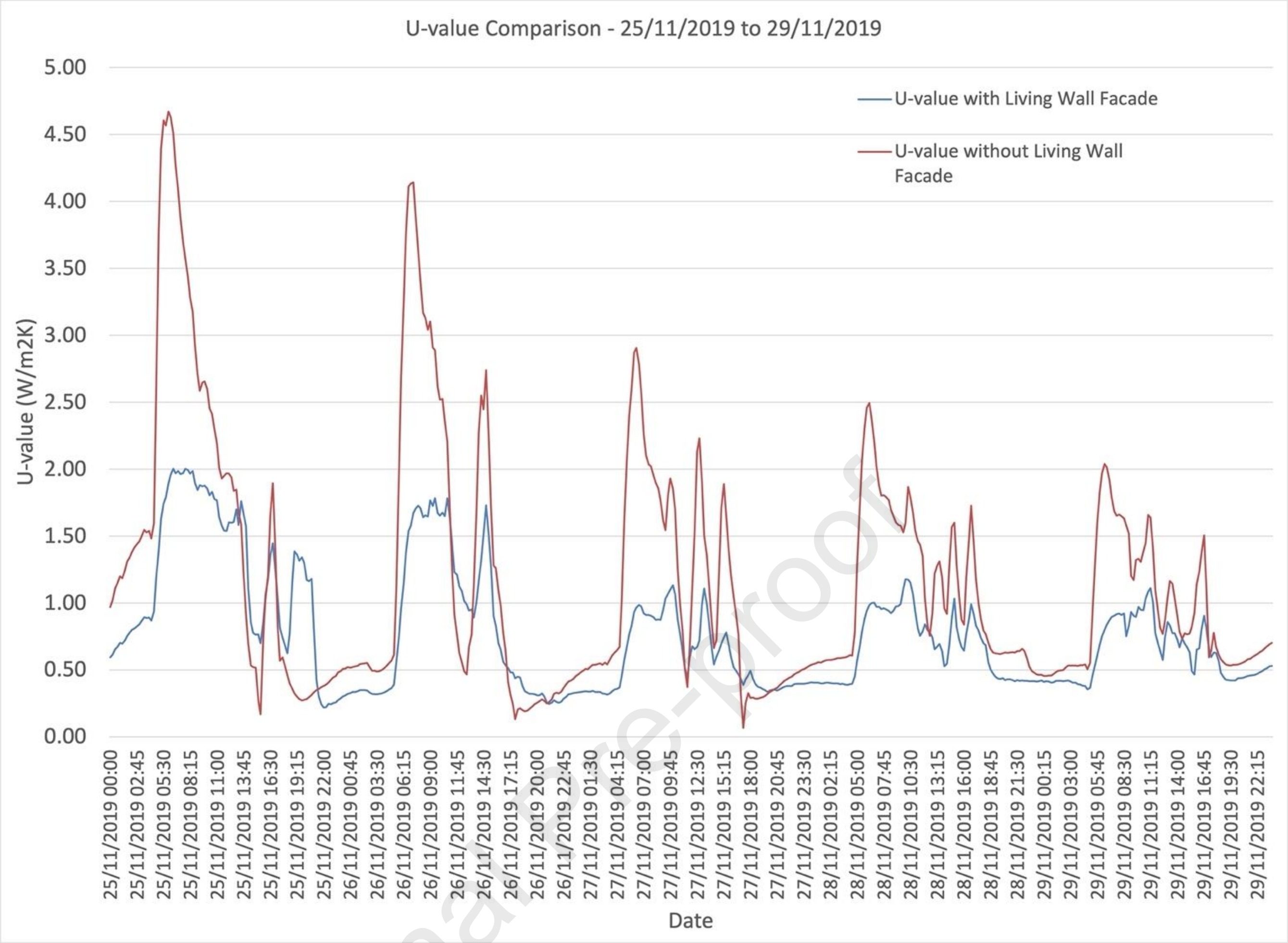

*Figure 6. 15-minute data interval U-value results for 5-day study selection.*

Following initial analysis on the 15-minute interval data, the data set was next calculated using Equation 2 to determine the moving average U-value for the two wall states. Results for each wall state are plotted in Figure 7 and show the moving average values plotted against the internal and external air temperatures. These results show how the moving average U-values began to level out after the first week of monitoring. This is likely due to the low variance in internal and external air temperature fluctuations. The most significant fluctuation being the drop in external air temperature to 1.5°C on the morning of Monday 2nd December.

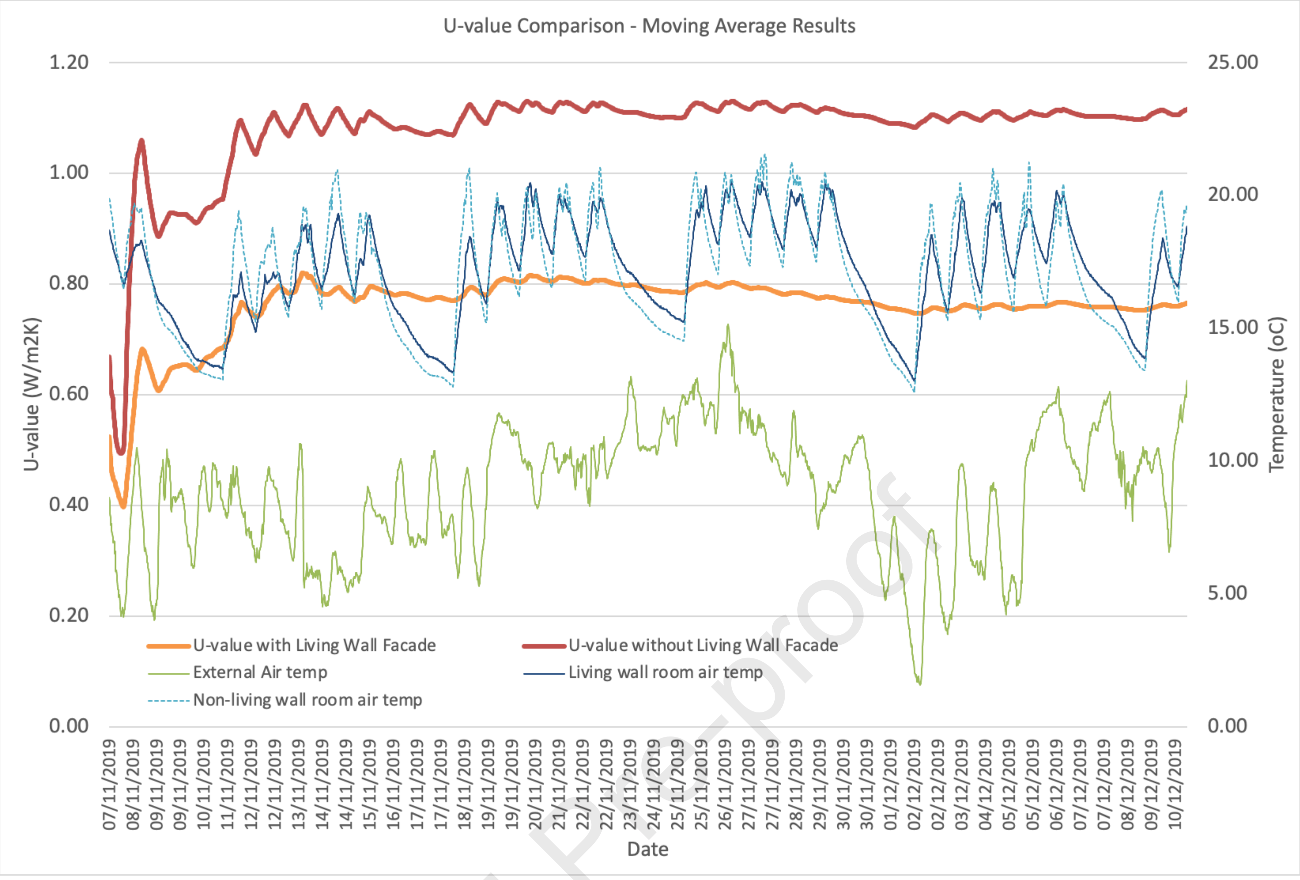

*Figure 7. Moving average U-value results for 5-week study period. Also showing internal and external air temperatures.*

At the end of the moving average calculation period a final U-value was recorded, which accounts for the full monitoring period. These were:

- Final U-value for cavity masonry wall with the living wall façade: 0.77W/m$^2$K
- Final U-value for cavity masonry wall without the living wall façade: 1.12W/m$^2$K

When compared with literature benchmarks, the measured U-value for the uninsulated masonry cavity wall compares well, as similar measurements by Baker [9] found U-values in the region of 1.3 to 1.1W/m$^2$K. This therefore places the study wall within Bakers' lower range for similar wall constructions. Furthermore, the existing walling performs better than estimated when calculated using theoretical data. This last point also serves to highlight the challenge when seeking to predict as-built / existing fabric U-values on existing buildings.

An alternative method to calculate a given wall's U-value is to undertake a desktop calculation in accordance with Anderson [16] per BS EN ISO 6946 [17]. Yet difficulties in ascertaining information such as the pre-existing brick and block types, and their specific thermal conductivity values could limit the accuracy and significance of such an exercise.

### 4.2 Uncertainty analysis

Measurements from heat flux analysis will contain a degree of inaccuracy, largely due to variables within the surrounding environment and monitoring equipment [73]. For this reason, uncertainty analysis of the in-situ U-value calculations were undertaken to better understand the potential for error. The method of uncertainty analysis used for these experiments was the 'root mean square' (RMS) method, which followed the approach used by Baker [9].

The sensitivity of each part of each equation was determined before conducting a RMS uncertainty equation. The resultant product indicated the uncertainty (±) of the calculated U-value.

For each measurement, an uncertainty, $\delta U$, can be introduced:

$$U_t \pm \delta U_t = \frac{\sum Q \pm \delta Q}{\sum((T_i \pm \delta T_i) - (T_e \pm \delta T_e))}$$

*Equation 3. Uncertainty analysis equation.*

To begin with, measurement errors were determined for each part of the applied equations and for the apparatus used. Accuracy data for the hardware gives uncertainties of ±5 % for $\delta Q$, recorded by the heat flux sensor [61] and ±0.21°C in the range of 0°C to 50°C for $\delta T_e$ and $\delta T_i$, recorded by the data loggers [74].

To perform the uncertainty analysis, each U-value equation was re-run, though this time each error was factored in, one at a time. Once all of the errors had been processed through the U-value equations, a RMS equation was conducted to derive the overall uncertainty of the U-value.

It should be noted that a greater degree of result uncertainty is to be expected from unknown constructions, or those with limited information. Ficco *et al.* [75] report on this issue, estimating an uncertainty of between 14% and 33% for constructions where material properties are unknown.

*Table 1. Uncertainty analysis for both wall states.*

| Wall State | Final moving average calculated U-Value (W/m2K) | U-value uncertainty ± (W/m2K) | Percentage uncertainty ± from calculated (%) |
|---|---|---|---|
| Masonry Cavity Wall **with** Living Wall Façade | 0.77 | 0.07 | 8.70% |
| Masonry Cavity Wall **without** Living Wall Façade | 1.12 | 0.10 | 8.71% |

Table 1**Error! Reference source not found.** shows that for each wall states the uncertainty in final moving average calculated U-value results were no more than ±0.10W/m2K. This degree of uncertainty corresponds with similar findings by [9], who calculate a ±0.11W/m2K (±8%) uncertainty for walls with a temperature difference between inside and outside of at least 8.3K. The temperature difference in this study was on average 8.26K.

## 5. Discussion

Initial comparison between the indoor air temperatures of the two separate rooms found that the larger room, which had the external living façade, presented narrower fluctuations in temperature variation compared with the room which did not have a living wall façade (figure 7). Whilst it is possible that the in-situ U-value for the two scenarios could be influenced by the different room temperatures, on closer analysis, the temperature difference between the two rooms was on average 0.3°C, and never exceeded a 2.5°C difference. The close similarity between room air temperatures was deemed to be of limited significance to the overall results.

Another factor that should be considered with the results is the location of the sensors in relation to the surrounding built forms. As previously discussed, care was taken to place all sensors in both locations with minimal variation in location differences. Whilst it was not possible to completely mitigate for variation, it is important to consider the un-controllable effects of such variations with this case study building. One example was the location of the non-living wall sensor close to an intersecting external wall. The effect of this external feature might have led to increased air turbulence at the corner. Lower air movement at this point might have resulted in an increased surface boundary layer and therefore variation in measured U-value.

As the review section of this paper indicates, a number of authors working in various fields suggest that green and living walls have the potential to provide a wide range of benefits both to the building occupants, and the local environment. Unfortunately, the review showed that there was less reliable information to guide a designer that might wish to assess how much an existing masonry building could be thermally improved in real conditions. Smaller scale results in more controlled environments can provide some precise measurement and associated themes that the study of a real building can then reflect and often substantiate.

From the case study findings it was found that by applying Equation 1 to each logged data interval, presented in Figure 5, it was clear that the U-value for the wall without the LWS cladding was greater than the wall which had the external living wall system. Analysing this further it became apparent that this was the case for 86.4% of all measurements. These initial findings suggest that the addition of a LWS could help to lower the heat loss from an external wall.

Figure 6 focuses in on a narrower 5-day band, presenting the difference in calculated results for each logged interval in greater clarity. It can also be seen from this graph how the diurnal temperature fluctuations for the wall with the LWS cladding is more gradual than the wall without the LWS cladding, which shows greater fluctuation over the same period. The patterns in heat loss at night for the two walls appears closer than experienced during the daytime. While this could be said to contradict findings by Nan et al. [40], who suggest that the insulating benefits from LWS might be expected in the evening or early morning, it might be explained by the use of the building. For instance, the heating period for this office building was during the day, with the heating system turned off during the evening, night and weekend periods. This is quite different to a domestic heating regime. The results therefore show that the greatest insulating benefit is had when the heating system is at its highest, which correlates with findings by Riley [33].

By reviewing the moving average results over the five-week study period (Figure 7), it became even more apparent that the final U-value for the wall with the addition of an external LWS façade was lower than the U-value for the wall without the LWS. This is significant, since it represents a 0.35W/m$^2$K improvement by simple addition of substrate and plant layer to the outside of the wall. This equates to a 31.4% improvement over the original wall state. Further investigations are planned that include assessments of the impact of different substrates and planting regimes upon the measured U value alongside connected variables such as irrigation schedules and variances in living wall moisture retention.

Comparisons can be made between the final U-value for the masonry wall with the LWS façade cladding and alternative insulation treatments, which could be applied to this masonry cavity wall construction. In a report for SAP, the BRE [76] present several options for cavity wall improvements. Starting with an average measured U-value for an un-insulated cavity wall of 1.43W/m$^2$K, for similar aged cavity walls (walls built before 1976), the BRE estimate that filling the empty cavity with insulation could bring the U-value down to 0.7W/m$^2$K.

A range of additional measures were presented in the BRE report, which brought the theoretical U-value down further, such as adding cavity insulation and internal or external insulation. However, the findings from this study have demonstrated that by adding a LWS façade to a similar aged masonry cavity wall, improvements in fabric U-value could match those expected from fully filling the cavity.

## 6. Conclusion

This paper has examined existing thermally related green and living wall research and in response to a lack of real building-based studies, explored the difference in thermal transmission between a pre 1970s uninsulated brick and block cavity wall and the same wall construction with a living wall system façade cladding fixed to the external face of the wall.

Overall findings from this study led to the calculation of a U-value for this LWS façade location, which was a 31.4% improvement over the original as built state of the same wall. Furthermore, analysis of the results showed that the diurnal fluctuations in U-value results were less varied over the study duration, with results varying by 2.05W/m$^2$K for the wall with the LWS façade compared with the standard state wall, which varied by 4.60W/m$^2$K over the same period.

Whilst this study is not representative of all situations and wall types, the findings suggest that adding a LWS to the façade of an uninsulated cavity masonry wall could be used to lower heat losses in addition to bringing many other benefits, such as increased biodiversity, sound absorption and reductions in air pollution.

The findings of this study suggest that there is a lack of empirical data on effects of living wall planting substrate on building insulation. The choice of planting substrate is potentially more significant to the insulation properties of living wall systems than plant choice. Substrates such as low-density soils with a high volume of air spaces and organic matter potentially provide increased thermal insulation in living wall systems.  Research by O'Donnell *et al.* [77] on arctic permafrost show clearly that the thermal conductivity of organic rich soils is typically lower than that of mineral soils. O'Donnell et al. [77] also show that thermal conductivity of soils is closely linked to moisture content, bulk density, and water phase within the soil.

The aspects that are highlighted alongside the work presented in this paper forms the basis for a larger study that will investigate the insulative benefits that an external living wall can deliver for existing buildings. As part of the larger study, future works shall explore the effect that organic matter has on thermal performance. Investigating the effect that irrigation has on soil conductivity, whether different plant species offer varied improvements in performance. Repeat investigations to this study will explore the effect that annual growth has on overall performance.

Further work is also required on the effect of plant type on building insulation and whether mixed species plantings are more or less effective in providing shade and thermal insulation than single species plantings. It is important that plant choice in living wall systems reflects not only the aesthetic requirements but maximises wider environmental and ecosystem service needs such as biodiversity enhancement, carbon sequestration as well as increasing building energy efficiency.

In addition, future work will monitor the temperatures at material boundaries throughout the entire construction to investigate the fluctuations throughout the layers. Investigations of the building's morphology shall also be investigated to better understand the positive or negative effects that wind movement might have on external walls with or without a living wall. Studies shall also be conducted on other buildings, construction types, different orientations and at different times of year to ascertain whether a living wall can deliver similar performance benefits to other buildings and in both heating and cooling seasons.

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**Declaration of interests**

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: