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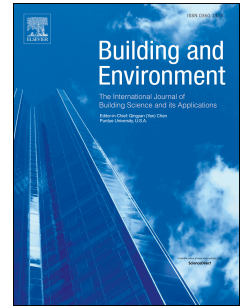
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1 Title Page

2 Title

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

4

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7

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10 Kingdom, PL4 8AA

11

12 Highlights

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

16

17 Abstract

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

22

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

29

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

35

36 Keywords

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

39

40 Abbreviations

41 Green Façade (GF), Living wall systems (LWS), Root mean square (RMS).

42 U-value presented in watts per meters squared, Kelvin (W/m^2K)

43

44 **Word count:** 6326

45

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48 commercial, or not-for-profit sectors.

49 1. Introduction

50

51 In Britain, buildings directly account for 17% of UK Greenhouse Gas Emissions (85 MtCO₂e in 2019)
52 [1], and space heating accounts for over 60% of all energy used in buildings [2]. Whilst modern policy
53 and construction methods strive to minimise energy use, it is acknowledged that there is a correlation
54 between the age of buildings and increased energy in use [3], with older buildings being the largest
55 contributors to carbon emissions.

56

57 Within England, approximately 57% all domestic [4] and non-domestic [5] buildings were built before
58 1964. Many other existing conurbations across the globe have similar rates of pre-existing buildings
59 and therefore are likely to have associated thermal standards within their existing building fabric.
60 Therefore if the UK is to reach its target of net zero carbon emission by 2050 [6, 7], and other global
61 targets it will be critical to address the energy use of existing building stock.

62

63 One of the most common forms of construction in the UK, some parts of Europe, North America and
64 Asia since the 1920s are masonry walls, with cavity systems accounting for around 70% of UK
65 dwellings [8]. The thermal performance of this form of construction is relatively poor, with measured
66 thermal transmission values in the region of 1.3 to 1.1W/m²K [9] and 1.56W/m²K [10] for masonry
67 cavity walls built before 1990. This date is significant, since the England and Wales building
68 regulations changed in 1990 to lower the thermal transmission value with nominal U-values for
69 external walls falling from 1.0W/m²K in 1976 to 0.45W/m²K in 1990 [11]. This led to increased use of
70 cavity fill insulation to meet the regulations. To date there are around 5.3 million UK properties (30%
71 of the total building stock) that do not have cavity insulation, many of which are perceived as being
72 hard to treat* [8]. *(Hard to treat infers associated difficulties in installing either cavity, internal or
73 external wall insulation to lower the wall's thermal transmission value).

74

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

80

81 Whilst insulation will reduce wall heat loss, it is estimated that wind driven convection can increase
82 heat loss from building surfaces by 50% [15]. This issue is recognised by Anderson [16] and BS EN
83 6946 [17], who estimate that exposed walls with a surface resistance of 0.04m²K/W can be improved
84 to between 0.1m²K/W and 0.13m²K/W (for high emissivity surfaces) if using some form of external
85 ventilated cladding / rain screen protecting the exposed surface. This could include the incorporation
86 of a container system used to provide the growing medium for housing plants close to an existing
87 wall.

88

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

97

98 There are many options available for external claddings on buildings, however a relatively new form
99 of external wall covering are 'green walls'. These green walls also known as 'vertical greening systems'

100 are typically categorised into Green Façade (GF) and living wall systems (LWS). Whilst GF use plants
101 directed to grow from a single point (usually at ground level) up a trellis or framework, LWS differ by
102 growing plants from multiple pockets of soil and other medium across the entire area of the façade
103 [20].

104
105 The aim of this paper is to investigate the potential for an external LWS to improve the fabric U-value
106 of existing cavity walls. This shall be investigated through these objectives:

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

110

111 2. Theory

112 Green wall systems offer a wide range of unique benefits [21] that more traditional inert façade
113 claddings such as timber or cementitious materials cannot provide. Benefits include enhanced sound
114 absorption [22], pollution mitigation and improvement in air quality [23], increased biodiversity [24],
115 added value from biodiversity [25], and psychological improvements from perceived organic aesthetic
116 [26, 27].

117

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

121

122 One area of previous research has focused on the reduction in the urban heat island effect in warm
123 climates, where foliage from such façades minimises the direct solar exposure on more traditional
124 thermally massive construction materials such as masonry [28], lowering the risk from re-emitted
125 thermal radiation to the urban realm. By minimising the solar gains on buildings, green walls have also
126 been found to lower the indoor air temperature of buildings in warm climates through foliage offering
127 shading to the façade [21]. Ottele et al., [15] explain how solar energy is used by the vegetation, with
128 5-30% being reflected, 5-20% used for photosynthesis, 10-50% turned into heat and 5-30%
129 transmitted through the leaf. They also add that 20-40% of the solar exposure is used for
130 evapotranspiration, which is the process of drawing heat through evaporated moisture from the leaf
131 [21]. The net result is that the ventilated air gap between the green wall and the adjoining
132 construction is cooled by the foliage restricting the path of solar energy to the building. This is
133 supported by Di & Wang [29] who found that peak cooling loads could be reduced by 28% for west
134 facing ivy covered walls when exposed to direct sunlight. Adding to this, Wong et al., [30] found that
135 wall surface temperatures could be reduced by over 11°C when using a vertical greenery system.
136 Work by Safikhani & Baharvand [31] explored the effect of increasing the ventilated cavity on
137 lowering wall surface temperatures, and found that a 30cm cavity on western located walls provided
138 the most optimal solution when utilising a green wall for cooling. Also work by Cameron et al., [32]
139 has explored the effect that different forms of foliage have on cooling.

140

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

151 *Luzula* spp. was 0.035 W/m.K with density of 210 kg/m³, which was closed to the commercial
152 insulator.

153

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

171

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

185

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

191

192 Leigh et al., [44] has shown that leaf morphology and anatomy has a significant influence on leaf
193 surface thermal dynamics. Smaller leaves with increasing leaf dissection (pinnate or bipinnate) were
194 found to have higher levels of heat dissipation [44] and reduce water loss [45]. Smaller, thicker more
195 dissected leaves can be an advantage to plants growing on water stressed vertical surfaces of
196 buildings but provide lower levels of shading from solar radiation [44]. Larger leaves provide higher
197 levels of shade [46] and could be important in minimizing excessively high heat loads on building
198 surfaces. Rupp and Gruber [43] model heat transfer for different leaf shapes and found that shape-
199 driven transfer enhancements were higher for models with small leaves with finely toothed edges,
200 with local cooling up to 10 °C below air temperature. Leaf surface is also important, increased leaf
201 surface pubescence (hair cover) and leaf margin complexity increase boundary layer thickness,

202 reducing leaf surface heating [43]. Pubescence and lighter-coloured leaves reflect more light
203 providing added leaf surface cooling and water conservation [45, 47]. When assessing all of these
204 variables Bau-Show Lin & Yann-Jou Lin [46] found that foliage density followed by leaf thickness, leaf
205 texture, and leaf colour had the greatest contribution to surface-soil cooling. Further work on living
206 wall systems is required to test these factors. There were some aspects that the review did not
207 provide definite answers to, such as the impact the type of organic matter has on thermal
208 performance. Similarly investigating the effect that irrigation has on soil and conductivity, whether
209 different plant species offer varied improvements in performance and exploring the effect that annual
210 growth has on overall performance. In some instances, this empirical data can be used to
211 model/simulate the possible building performance outcomes associated with different
212 plant/layout/substrate and existing walling options.

213
214 Many studies have focused on modelling [48, 49], simulation [42, 50-54], multi-layer temperatures
215 [30, 37, 55] and humidity [40] monitoring; however, few have used in-situ heat flux to assess thermal
216 conductivity through LWS. Of those who have used heat flux methodologies, Mazzali et al., [56] have
217 investigated the rate of heat flux through foliage to the masonry wall behind. This was to assess the
218 cooling properties of a LWS. In another study, Manso & Gomes [57] investigated a cork-based LWS
219 attached to an insulated metal building in Portugal. Over three 14-day periods, they utilised
220 temperature and heat flux monitoring. Results were promising and found that minimum internal
221 surface temperatures could be increased by 7°C during winter periods with the addition of the cork
222 based LWS. Additional work using heat flux investigations on LWS in a winter period was conducted
223 by Tudiwer & Korjenic [58]. In this study, two types of living wall were investigated and compared
224 with un-covered sections of wall. Results found that the LWS monitored gave between 0.13m²K/W
225 and 0.68m²K/W improvement in thermal resistance over non-greened walls. These findings are also
226 promising and suggest that further work on different types of LWS is needed to better understand the
227 winter period improvements that can be made by installing these systems to an existing building.

228
229 Despite previous work in this field, there remains a lack of research investigating the thermal
230 performance improvement that could be made to a traditional masonry cavity wall. In the UK, this is
231 significant, given the large number of existing masonry cavity walls present. Whilst traditional
232 strategies for improving the thermal resistance of such walls might have added insulation, literature
233 suggests that LWS could offer an alternative solution for thermal improvement, whilst also providing
234 other unique benefits such as biodiversity, aesthetic and air quality improvements. Furthermore,
235 understanding the scale of the thermal improvement offered in this setting will help define the
236 sustainability potential of this approach given the potentially high environmental lifecycle and overall
237 energy burden this system may exert [15].

238
239 Due to the limited research on thermal performance improvement from LWS on masonry cavity walls,
240 a practical development from this theory was deemed necessary.

241
242 The following sections present an investigation into the thermal performance of an externally applied
243 LWS façade cladding treatment placed over an existing uninsulated masonry cavity wall. The setting
244 for this is Plymouth, UK, which is sited in a maritime climate. The objective will be to compare two
245 identical sections of existing walling (one covered with the living wall) using heat flux sensors to
246 determine whether any improvement can be made with the selected living wall system.

247

248 **3. Material and Methods**

249

250 **3.1 The case study building**

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

253 18th Century and has since been extended over the years to convert into an office building. Reflecting
254 this historic development, the construction comprises of a variety of materials, though the external
255 walls were a mixture of rendered solid stone and uninsulated rendered brick / block (Masonry) cavity
256 walling.

257
258 In 2019 this building received extensive internal and external renovation. Whilst this regime of
259 improvements did not include additional insulation to the external walls, one major intervention was
260 the installation of an externally planted living wall.

261
262 The living wall used for this building is the modular 'Fytotextile' system, which was supplied by
263 Scotscape [59]. This flexible felt fabric sheet system is made up of waterproof synthetic layer,
264 absorbent moisture layer (middle layer) and porous outer felt layer and makes use of these to form
265 pockets for soil and planting. The tested LWS uses a mixture of evergreen plant types including sedges
266 (*Carex spp*), ferns (e.g. *Dryopteris spp*), rushes (e.g. *Luzula spp*) and flowering shrubs (e.g. *Sarcococa*
267 *confusa*). Plants were installed with a standard multi-purpose potting compost. These fytotextile
268 sheets are fixed to the wall via a frame and plants are watered using a tubular drip-irrigation system
269 from above the sheets. Figure 1 shows a photograph of the system used in this study.

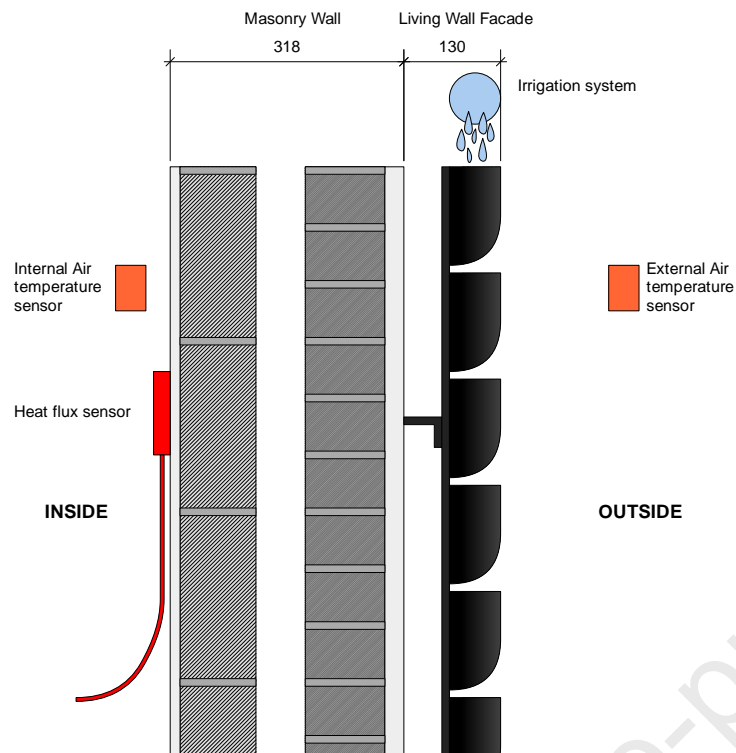
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271

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

273



274
275 *Figure 2. Cross section through the wall showing diagrammatic location of sensors.*
276

277 The living wall was installed on the west and south elevations to the building. These elevations were
278 selected for their ease of retrofit and comprised of masonry cavity wall construction. Figure 2
279 presents a section through the cavity wall, showing the attachment of the Fytotextile living wall
280 system. Figure 3 shows a photo of the case study building, which illustrates the extent of the living
281 wall system.
282



283
284 *Figure 3. Photo of case study building, showing locations of monitoring setup.*

285

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

289

290 Illustrated in figure 2, the existing wall comprised of an inner leaf of dense concrete block (125mm)
 291 and an outer leaf of brick (105mm). These layers were separated by a 50mm uninsulated cavity. The
 292 internal face of the wall was finished with a gypsum plaster (13mm). The external face of the wall was
 293 finished with a painted render finish (25mm). The render had a rough cast finish. The exact physical
 294 properties of these materials were not known due to the limited access for destructive investigation,
 295 however it is possible to estimate the theoretical U-value, calculated from data provided by CIBSE
 296 [60]. Using a medium density concrete block at 0.77W/mK and external leaf brick at 0.84W/mK, with
 297 a cementitious render (1.13W/mK) and gypsum plaster (0.18W/mK), a predicted U-value for the wall
 298 could be calculated to be 1.37W/m²K.

299

300 3.2 Monitoring methodology

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

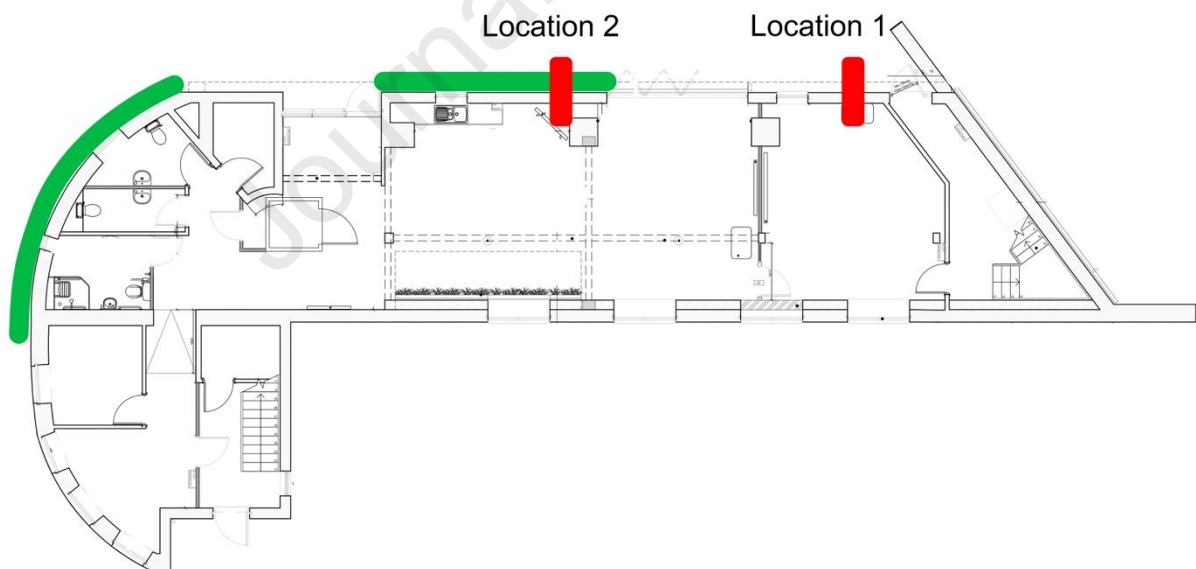
304

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

307

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

310



311

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

314

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

319

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

329

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

333

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

342

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

346

347 Each set of heat flux sensors were connected to a calibrated Campbell Scientific CR1000 data logger
348 [69], which were used to collect data for the experimental period. At the end of the experiment, the
349 data was downloaded and analysed to determine the in-situ U-value.

350

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

354

355 The methodology for the heat flux experiment was developed in accordance with ISO 9869-1:2014
356 [63], and previous work by Asdrubali *et al.* [70] and Baker [9, 64]. For the monitoring period a 15-
357 minute temporal resolution for data collection was selected. All the apparatus was coordinated so
358 that measurements were recorded at the same time. In selecting the duration of the experimental
359 period, Biddulph *et al.* [71] recommend a three week data collection period, while Baker [64]
360 recommends monitoring for 27 days. Because the building being inspected would be in constant use
361 during the experiment, it was decided that a five-week data collection period would be used.

362

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

368

369 **3.3 Analysis equation**

370 Data from all sources of apparatus was downloaded at the end of the monitoring period and collated
 371 in excel where it was reviewed to calculate the moving average thermal transmission for each section
 372 of walling. [61-63]. The equation used was taken from the BRE average method for in-situ U-value
 373 calculation [62]:
 374

$$375 \quad U = \frac{Q}{T_i - T_e} = \frac{Q}{\Delta T}$$

376
 377

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

379

380 In order to evaluate the thermal transmission over time, this equation can be modified to take
 381 account of consecutive data in a moving average equation:
 382

383

384

385

$$386 \quad U_t = \frac{\sum Q_i}{\sum (T_i - T_e)_i} = \frac{\sum Q_i}{\sum \Delta T_i}$$

387

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

389

390 Where:

391 U_t = Average U-value over t hours (W/m^2K)

392 $\sum Q_i$ = Heat flux at interval of i hours (W/m^2)

393 $\sum \Delta T_i$ = Temperature difference between internal and external space at interval of i hours (K)

394

395 4. Results

396 4.1 Monitoring results

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

398

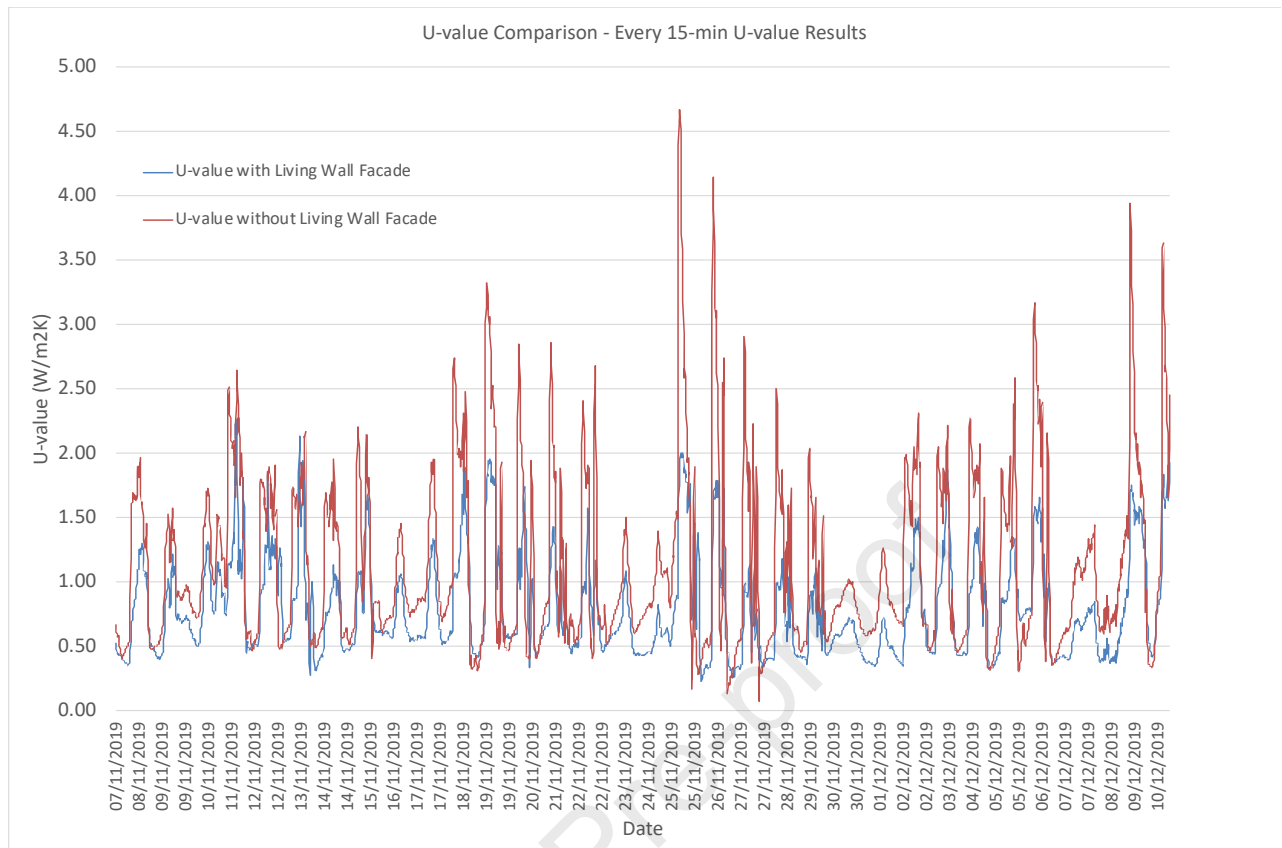
399 Internal air temperature results presented a pattern that clearly showed when the space heating
 400 turned on and off during a daily cycle. Weekends were distinguishable due to the absence of space
 401 heating during this two-day period. The average internal air temperature for this study period was
 402 $17.2^\circ C$ ($\pm 4.2^\circ C$ fluctuations). External air temperatures varied from between $5^\circ C$ and $12^\circ C$ during the
 403 study period, with a high of $15^\circ C$ and low of $1.5^\circ C$. The average external air temperature was $8.9^\circ C$
 404 ($\pm 6.8^\circ C$ fluctuations).
 405

406

406 *The 15-minute spaced data interval was calculated using U-value*

407 Equation 1 as a first step to analysis. The results from this are presented in Figure 5.

408



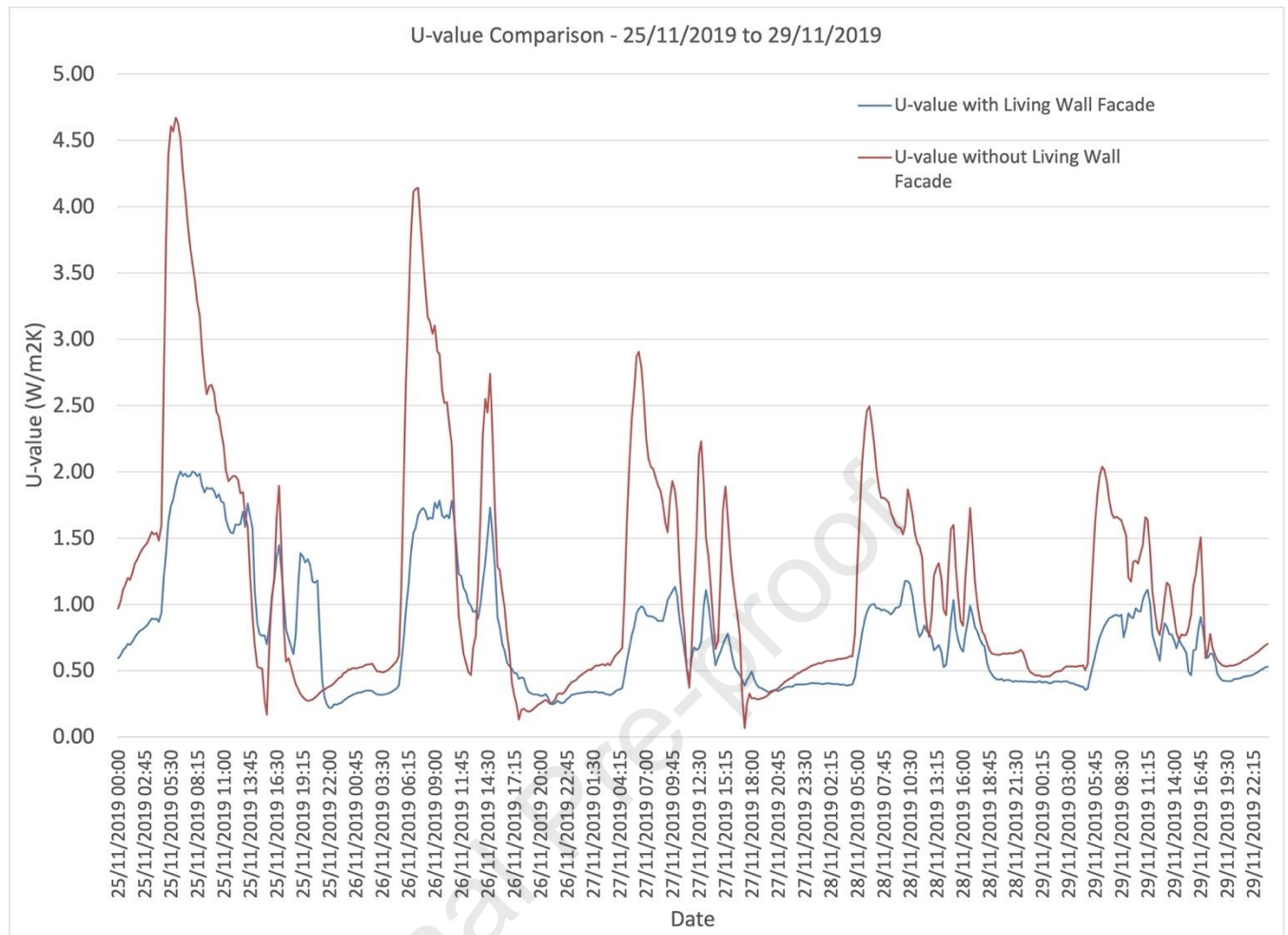
409
410 *Figure 5. 15-minute data interval U-value results for 5-week study period.*

- 411
412 Uninsulated masonry wall without living façade
- 413 • Highest measured U-value: 4.67W/m²K
 - 414 • Lowest measured U-value: 0.07W/m²K
 - 415 • Spread between values: 4.60W/m²K

- 416
417 Uninsulated masonry wall with living façade
- 418 • Highest measured U-value: 2.26W/m²K
 - 419 • Lowest measured U-value: 0.22W/m²K
 - 420 • Spread between values: 2.05W/m²K

421
422 Figure 6 takes a five-day period from Monday 25th to Friday 29th November and focuses in more detail
423 to observe the fluctuations of each wall state over a shorter period. This shows the difference in
424 measurement fluctuations between the two wall states.

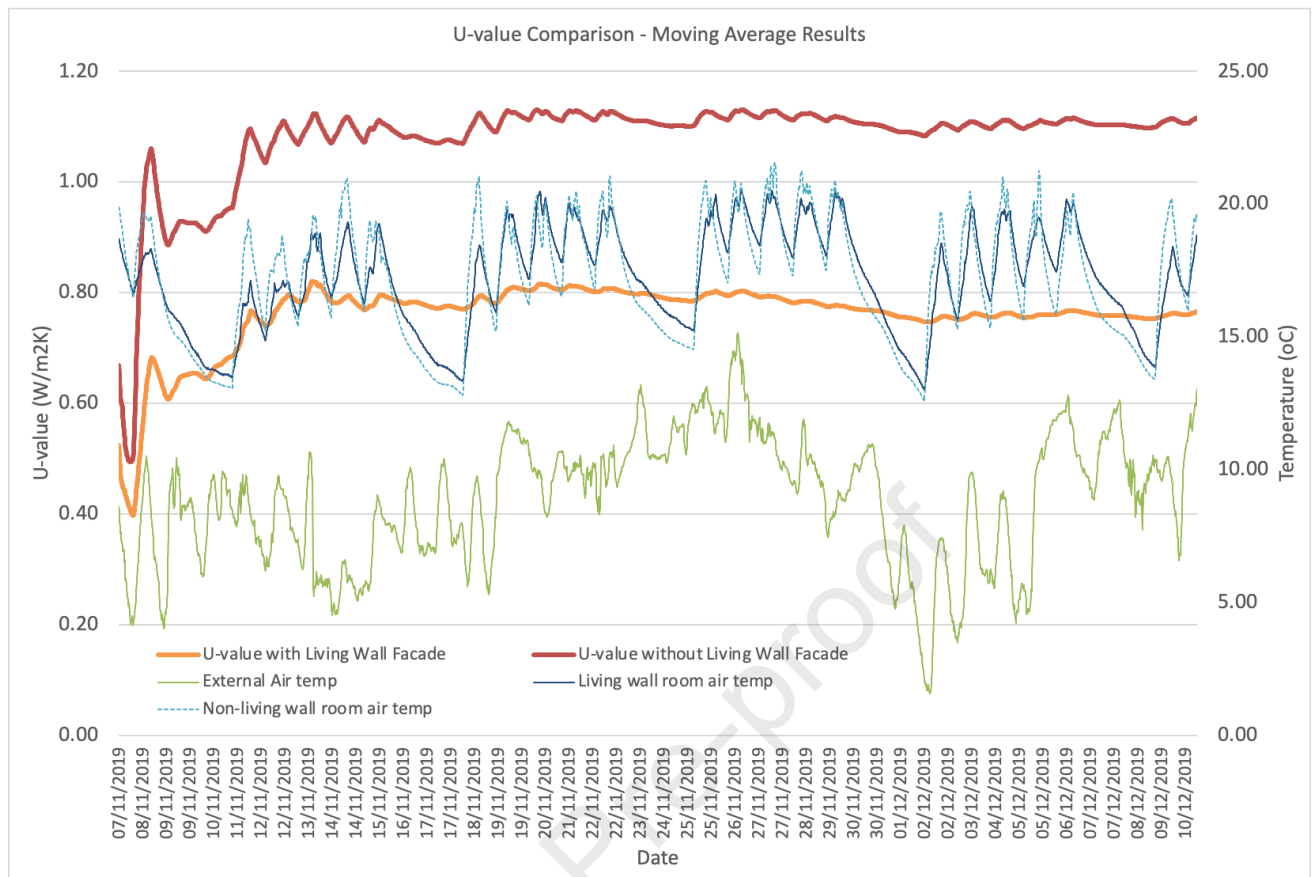
425



426
427 *Figure 6. 15-minute data interval U-value results for 5-day study selection.*

428
429 Following initial analysis on the 15-minute interval data, the data set was next calculated using
430 Equation 2 to determine the moving average U-value for the two wall states. Results for each wall
431 state are plotted in Figure 7 and show the moving average values plotted against the internal and
432 external air temperatures. These results show how the moving average U-values began to level out
433 after the first week of monitoring. This is likely due to the low variance in internal and external air
434 temperature fluctuations. The most significant fluctuation being the drop in external air temperature
435 to 1.5°C on the morning of Monday 2nd December.

436



437
438 *Figure 7. Moving average U-value results for 5-week study period. Also showing internal and external*
439 *air temperatures.*

440
441 At the end of the moving average calculation period a final U-value was recorded, which accounts for
442 the full monitoring period. These were:

- 443
- 444 • Final U-value for cavity masonry wall with the living wall façade: $0.77\text{W/m}^2\text{K}$
 - 445 • Final U-value for cavity masonry wall without the living wall façade: $1.12\text{W/m}^2\text{K}$
- 446

447 When compared with literature benchmarks, the measured U-value for the uninsulated masonry
448 cavity wall compares well, as similar measurements by Baker [9] found U-values in the region of 1.3 to
449 $1.1\text{W/m}^2\text{K}$. This therefore places the study wall within Bakers' lower range for similar wall
450 constructions. Furthermore, the existing walling performs better than estimated when calculated
451 using theoretical data. This last point also serves to highlight the challenge when seeking to predict
452 as-built / existing fabric U-values on existing buildings.

453
454 An alternative method to calculate a given wall's U-value is to undertake a desktop calculation in
455 accordance with Anderson [16] per BS EN ISO 6946 [17]. Yet difficulties in ascertaining information
456 such as the pre-existing brick and block types, and their specific thermal conductivity values could
457 limit the accuracy and significance of such an exercise.

458 459 **4.2 Uncertainty analysis**

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

465
466 The sensitivity of each part of each equation was determined before conducting a RMS uncertainty
467 equation. The resultant product indicated the uncertainty (\pm) of the calculated U-value.
468

469 For each measurement, an uncertainty, δU , can be introduced:
470

$$471 \quad U_t \pm \delta U_t = \frac{\sum Q \pm \delta Q}{\sum((T_i \pm \delta T_i) - (T_e \pm \delta T_e))}$$

472 *Equation 3. Uncertainty analysis equation.*
473

474
475 To begin with, measurement errors were determined for each part of the applied equations and for
476 the apparatus used. Accuracy data for the hardware gives uncertainties of $\pm 5\%$ for δQ , recorded by
477 the heat flux sensor [61] and $\pm 0.21^\circ\text{C}$ in the range of 0°C to 50°C for δT_e and δT_i , recorded by the
478 data loggers [74].
479

480 To perform the uncertainty analysis, each U-value equation was re-run, though this time each error
481 was factored in, one at a time. Once all of the errors had been processed through the U-value
482 equations, a RMS equation was conducted to derive the overall uncertainty of the U-value.
483

484 It should be noted that a greater degree of result uncertainty is to be expected from unknown
485 constructions, or those with limited information. Ficco *et al.* [75] report on this issue, estimating an
486 uncertainty of between 14% and 33% for constructions where material properties are unknown.
487

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

Wall State	Final moving average calculated U-Value (W/m ² K)	U-value uncertainty \pm (W/m ² K)	Percentage uncertainty \pm 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%

489
490 Table 1 **Error! Reference source not found.** shows that for each wall states the uncertainty in final
491 moving average calculated U-value results were no more than $\pm 0.10\text{W/m}^2\text{K}$. This degree of
492 uncertainty corresponds with similar findings by [9], who calculate a $\pm 0.11\text{W/m}^2\text{K}$ ($\pm 8\%$) uncertainty
493 for walls with a temperature difference between inside and outside of at least 8.3K. The temperature
494 difference in this study was on average 8.26K.
495

496 5. Discussion

497 Initial comparison between the indoor air temperatures of the two separate rooms found that the
498 larger room, which had the external living façade, presented narrower fluctuations in temperature
499 variation compared with the room which did not have a living wall façade (figure 7). Whilst it is
500 possible that the in-situ U-value for the two scenarios could be influenced by the different room
501 temperatures, on closer analysis, the temperature difference between the two rooms was on average
502 0.3°C , and never exceeded a 2.5°C difference. The close similarity between room air temperatures
503 was deemed to be of limited significance to the overall results.
504

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

513

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

521

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

528

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

540

541 By reviewing the moving average results over the five-week study period (Figure 7), it became even
542 more apparent that the final U-value for the wall with the addition of an external LWS façade was
543 lower than the U-value for the wall without the LWS. This is significant, since it represents a
544 $0.35\text{W/m}^2\text{K}$ improvement by simple addition of substrate and plant layer to the outside of the wall.
545 This equates to a 31.4% improvement over the original wall state. Further investigations are planned
546 that include assessments of the impact of different substrates and planting regimes upon the
547 measured U value alongside connected variables such as irrigation schedules and variances in living
548 wall moisture retention.

549

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

556

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

561

562 6. Conclusion

563 This paper has examined existing thermally related green and living wall research and in response to a
564 lack of real building-based studies, explored the difference in thermal transmission between a pre
565 1970s uninsulated brick and block cavity wall and the same wall construction with a living wall system
566 façade cladding fixed to the external face of the wall.

567

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

573

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

578

579 The findings of this study suggest that there is a lack of empirical data on effects of living wall planting
580 substrate on building insulation. The choice of planting substrate is potentially more significant to the
581 insulation properties of living wall systems than plant choice. Substrates such as low-density soils with
582 a high volume of air spaces and organic matter potentially provide increased thermal insulation in
583 living wall systems. Research by O'Donnell *et al.* [77] on arctic permafrost show clearly that the
584 thermal conductivity of organic rich soils is typically lower than that of mineral soils. O'Donnell *et al.*
585 [77] also show that thermal conductivity of soils is closely linked to moisture content, bulk density,
586 and water phase within the soil.

587

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

594

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

600

601 In addition, future work will monitor the temperatures at material boundaries throughout the entire
602 construction to investigate the fluctuations throughout the layers. Investigations of the building's
603 morphology shall also be investigated to better understand the positive or negative effects that wind
604 movement might have on external walls with or without a living wall. Studies shall also be conducted
605 on other buildings, construction types, different orientations and at different times of year to

606 ascertain whether a living wall can deliver similar performance benefits to other buildings and in both
 607 heating and cooling seasons.

608

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Journal Pre-proof

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:

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