

Comparative experimental approach to investigate the thermal behaviour of vertical greened façades of buildings

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3 **Comparative experimental approach to investigate the thermal behaviour of vertical**
4 **greened façades of buildings**

5
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10
11 **Abstract**

12 Greening the building envelope is not a new concept, however it has not been fully approved as
13 an energy saving method for the built environment. Vertical green can provide a cooling potential
14 on the building surface, as plants are functioning as a solar filter and prevent the adsorption of
15 heat radiation of building materials extensively. In this study a comparative thermal analysis of
16 vertical green attached to a façade element is presented. An experimental set up (stationary
17 conditions) has been developed to measure the temperature gradient through a reference cavity
18 wall, in order to quantify the contribution of vegetation to the thermal behaviour of the building
19 envelope. The results show temperature differences between the bare wall and between the
20 different vertical greening systems analysed, up to 1.7 °C for the direct greening system and
21 8.4°C for the living wall system based on planter boxes after 8 hours of heating for summer
22 conditions, due to the different “material” layers involved. However, the insulation material of the
23 bare wall moderates the prevailing temperature difference between the outside and inside climate
24 chamber, resulting in no temperature difference for the interior climate chamber for summer
25 conditions.

26
27
28 **Keywords:** vertical greening, green facades, building envelope, climate chamber, thermal
29 behaviour, cooling, insulation

30
31
32 **1. Introduction**

33 In dense urban areas the prevalence of paved surfaces (with low albedo) and a lack of natural
34 vegetation are among the major causes of the phenomenon called urban heat island effect:
35 temperature difference between cities and suburban or rural areas is determined by this
36 phenomenon [1], [2]. Introducing vegetation back in our cities is a possibility to alter the
37 microclimate in street canyons [3], [4]. Greened paved surfaces intercept solar radiation and can

38 reduce warming of artificial surfaces as asphalt or concrete, thus reducing the urban heat island
39 phenomenon by two to four degrees Celsius [5], [6]. Outer surfaces of buildings offer a great and
40 unused amount of space for re-introducing vegetation in our cities; green roofs and green façades
41 are possibilities to fulfil this opportunity [7].

42 Vertical greening systems have a positive influence on the building envelope in terms of thermal
43 performances, as demonstrated by several studies [8], [9]. Hunter et al. [10] show that green
44 façades, like other forms of green infrastructure, are increasingly being considered as a design
45 feature to cool internal building temperatures, reduce building energy consumption and facilitate
46 urban adaptation to a warming climate. In the beginning of the eighties Krusche et al. [11]
47 estimate the thermal transmittance (U) of a 160 mm plant cover at $2.9 \text{ Wm}^{-2}\text{K}^{-1}$. Also Minke et al.
48 [12] suggested some ideas to reduce the exterior coefficient of heat transfer. By reducing the
49 wind speed along a green façade they suggested that the exterior coefficient of heat transfer of
50 $25.0 \text{ Wm}^{-2}\text{K}^{-1}$ can be lowered to $7.8 \text{ Wm}^{-2}\text{K}^{-1}$ which is comparable to the interior coefficient of heat
51 transfer. Holm [13] shows with field measurements and his DEROB computer model the thermal
52 improvement potential of leaf covered walls. A layer of vegetation, as a green façade made of
53 *Hedera helix* can enhance the thermal performances of buildings also during winter season [14].
54 The authors found the largest savings in energy due to vegetation associated with more extreme
55 weather, such as cold temperatures, strong wind or rain, increasing energy efficiency by 40-50%
56 and enhancing wall surface temperatures by 3°C. Perini et al. [15] show the influence of a green
57 layer on the reduction of the wind velocity along the surface of a building. An extra stagnant air
58 layer in optimal situations can be created inside the foliage, so that when the wind speed outside
59 is the same as inside R_{exterior} can be equalized to R_{interior} , where R is the thermal resistance
60 ($\text{m}^2\cdot\text{K}\cdot\text{W}^{-1}$). In this way the building's thermal resistance can be increased by $0.09 \text{ m}^2\cdot\text{K}\cdot\text{W}^{-1}$.
61 Vertical greening systems insulation value can be optimized by covering with high density foliage,
62 creating a stagnant air layer behind the foliage [15], exploiting supporting system materials and
63 their insulation effect and plant species characteristics [14].

64 Eumorfopoulou et al. [16] reported the temperature cooling potential of plant covered walls in a
65 Mediterranean climate; the effect was up to 10.8 °C. Another recent study by Wong et al. [17] on
66 a free standing wall in Hortpark (Singapore) with vertical greening types shows a maximum
67 reduction of 11.6 °C. The green plant layer will also reduce the amount of UV light that will reach
68 building materials, since by constructing green façades great quantities of solar radiation will be
69 adsorbed for the growth of plants and their biological functions [11]. Since UV light deteriorates
70 the mechanical properties of coatings, paints, plastics, etc. plants will also affect durability
71 aspects of constructions [17]. However, in the case of green façade directly attached, climbing
72 plants may deteriorate the building envelope outer layer, especially in the case of plaster walls
73 [18], [19]

74 Susorova et al. [20] demonstrate that façade orientation plays an important role as well for

75 cooling capacity due to shadow and evapotranspiration provided by plants. In addition, studies
76 show a potential energy saving for air conditioning that can be obtained with vertical greening
77 systems up to 40-60% in Mediterranean area [3], [21]–[24]
78 The discussed studies, showing the potential effects of vertical greening systems on the
79 microclimate, are all done under variable environmental conditions.

80

81 The present study aims to classify the thermal benefits of green façades or plant covered
82 cladding systems under boundary conditions. The results of this study can be used for giving
83 evidence of the effects of vertical green as an “extra insulation” layer”, to support the decision
84 process for architects, building owners, etc. This “technical/thermal green” strategy of increasing
85 exterior insulation properties of vertical surfaces stimulates upgrading or retrofitting of existing
86 (under-insulated) façades without the added cost of interior or traditional exterior insulation
87 systems. An insulation material mitigates the impact of the created temperature difference
88 between inside and outside [25]. In the research work done by Eumorfopoulou and Aravantinos
89 [26], it was found that a planted roof contributes to the thermal protection of a building but that it
90 cannot replace the thermal insulation layer. From a scientific point of view it is relevant to verify if
91 this effect is also valid for green façades.

92 A comparison between a bare façade and a plant covered façade is investigated in order to
93 quantify the contribution of vegetation to the thermal behaviour of the building envelope, with
94 three different greening systems applied (a direct green façade and two different living wall
95 systems), during summer and winter seasons.

96 The experimental study aims at identifying differences between the bare wall and between the
97 different vertical greening systems, due to the different layers involved (a biotic and biotic
98 components).

99 The experiment presented seeks at analysing the relation between vegetation and the built
100 environment. In particular it is focused on the possible contribution of vertical greening systems in
101 improving the thermal behaviour of the building envelope.

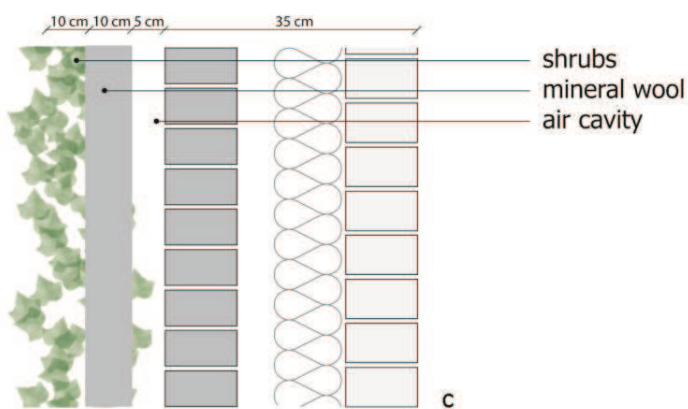
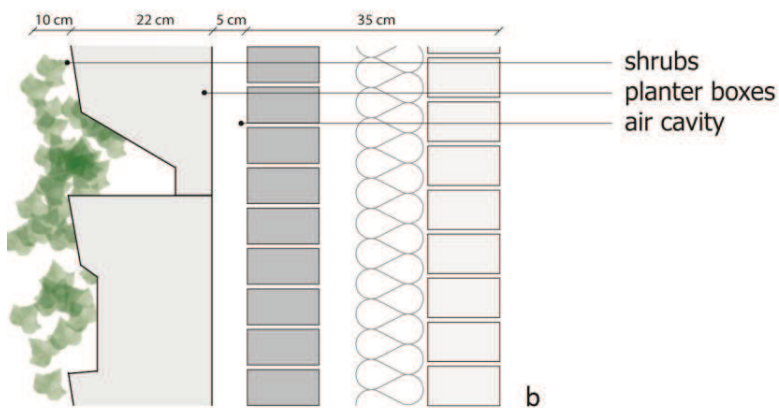
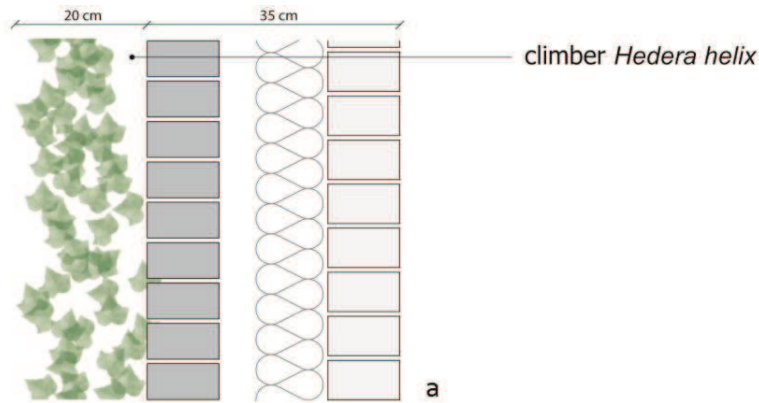
102 The main objective of the presented study is to measure the temperature gradient through a
103 vertical greened façade element, to quantify the thermal resistance of vertical greening systems
104 and to understand the thermal behaviour in warm (up to 35°C) and cold conditions (down to -5°C).

105

106 **2. Experimental set up and methodology**

107 This research describes a procedure for comparative measurements of steady-state (stationary
108 condition) heat transfer through a cavity wall with three different vertical greening systems:
109 *Hedera helix* directly to the wall and two living wall systems are based on mineral wool and
110 planter boxes. The bare wall configuration serves as a reference measurement, besides it gives
111 information over the total energy performance of the composite façade when it is covered with

112 vertical green. The living wall system based on planter boxes uses *Lamium galeobdolon*, *Carex*,
 113 *Alchemilla*, and *Hosta*, the one based on mineral wool: *Ferns*, *Geraniums*, and *Carex*. According to
 114 Perini et al. [27], although species have different evaporation capacities, which affect the cooling
 115 effect, the major role is played by the supporting system itself. The analysis of these greening
 116 systems using different configurations, layers and materials will provide useful information about
 117 the influence of the systems' characteristics on thermal performances. The bare wall stratigraphy
 118 analysed represents a typical/common European building envelope.



119

120 Figure 1 Vertical greening systems analysed in the study: (a) direct green façade, (b) living wall
121 system based on planter boxes, (c) living wall system based on mineral wool.



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133 Figure 2 Cross section of the vertical greening systems analysed in the study (a) direct green
134 façade, (b) living wall system based on planter boxes, (c) living wall system based on mineral
135 wool.

136
137 The designed apparatus – called “hot box” – is intended to reproduce different boundary
138 conditions of a specimen between two different environments, in the presented research is
139 chosen for an “indoor” and “outdoor” environment. A digital temperature controller and convective
140 heater as well as infrared radiation bulbs maintain the box temperature as close as possible to
141 environmental outdoor conditions. The total energy input represents the heat transfer through the
142 test system. An automatic data collection system is used in this experiment, so that tests can be
143 conducted over a long period of time (if needed) to assure steady-state conditions and to
144 determine reproducibility of the laboratory measurements.

145 This study investigates the effects of vertical greening systems in warm (up to 35°C) and cold
146 conditions (down to -5°C). For this reason, representative days are chosen and analysed
147 (according to e.g.[28]). Each system was measured 3 times for summer and winter condition. The
148 summer measurements are conducted over a time span of 8 hours when it is assumed to reach a
149 steady state situation. The winter measurements are conducted over a larger time span of 72
150 hours to reach a steady state situation.

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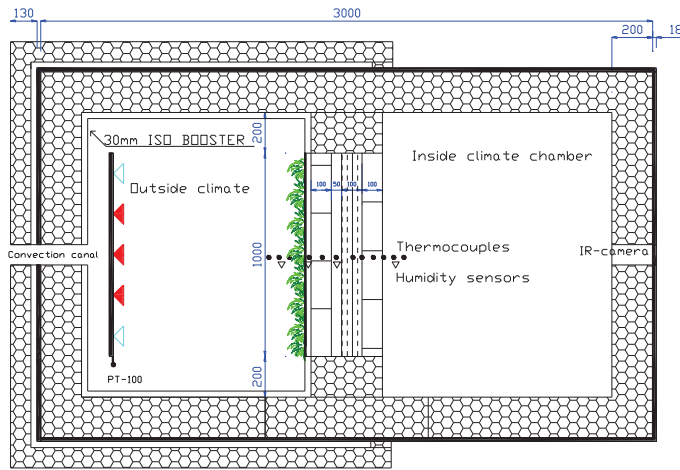
153 **2.1 Experimental details of the climate chamber**

154 The climate chamber used in this experiment was designed and constructed according to NEN-
155 EN 1934. The standard requires a “hot” chamber on one side of the tested specimen and a heat
156 sink in the form of a “cold” chamber in which environmental conditions are imposed.

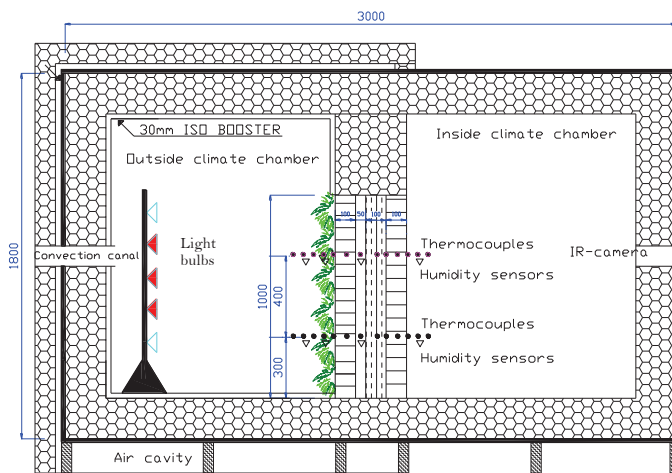
157 The constructed box (the so called “outside and inside” climate chamber) is insulated from its
 158 surroundings using 200 mm (two layers overlapped of 100 mm) of expanded polystyrene
 159 insulation (EPS) insulation material, with a conductivity of 0.036 W/m.K. The two layers of EPS
 160 are glued together and fixed to a plywood face of 18 mm in order to get some stiffness between
 161 the panels. In the so called “outside” climate chamber extra insulation material is attached to the
 162 EPS in order to minimize heat loss. For this application ISOBOOSTER-T1 sheets of 240 mm
 163 thickness are used with a U - value of 0.42 W/m²·K. The outside and inside climate chambers
 164 have the same dimensions and are as follows (figures 3 and 4):

- 165 - length $L = 1.10$ m
- 166 - width $w = 1.40$ m
- 167 - height $H = 1.40$ m

168



169



170

171 Figure 3 top view and cross section view of the designed box and the positions of the
 172 thermocouples used; dimensions in mm.

173

174 In the middle of the box a cavity wall is constructed as reference material and to test vertical
175 greening systems placed in front of it (figure 4). The cavity wall also directly forms a sample
176 holder for vertical green cladding systems. For the living wall systems an air cavity is created
177 between living wall panel and the façade (figure 1).
178



179
180 Figure 4 side and front view of the constructed cavity wall used for the experiments.

181
182 In this way the box is divided into two chambers: an “outside” climate chamber and an “inside”
183 climate chamber as it is mentioned in the text. In order to minimize the heat loss through the walls
184 of the “outside” climate chamber, an extra insulation layer of 100 mm EPS with an air cavity of 30
185 mm is constructed at the outside of the box (only around the outside climate chamber). This extra
186 layer serves as a guard by keeping the temperature of the air cavity the same as temperature in
187 the “outside” climate chamber. The guard section ensures that the lateral heat flow rate from the
188 outside chamber is nearly zero to the guard section. The relative humidity in the climate chamber
189 was measured by Honeywell hygrometers with a thermoset polymer capacitive sensing element
190 during the experiments to exclude the influence of evapotranspiration of the different green
191 systems. The relative humidity in the “outside” climate chamber was brought to 85% with an
192 electric Honeywell ultrasonic air humidifier before the measurement was started.

193 The temperature of the guard section (extra air cavity) is controlled with a PT100 in combination
194 with an ENDA ET1411 digital thermostat temperature controller (connected to a solid state relay).
195 The box tightness (thermal leakage) inside and outside the box was determined by the use of an
196 infrared camera (FLIR A320).

197
198 Temperature measurements were made using thermocouples and PT100 sensors. Amount and
199 position of the thermocouples is given in table 1 and schematically presented in figure 3. The data
200 is collected and recorded on a data logger with a frequency of acquisition of 60 scans per hour.
201 The total system is controlled by a personal computer. In order to study the effect of convection
202 (warm air) and radiation (sunshine) on the heat transfer trough a greened wall both are tested
203 separately.
204

205 Control system convection and radiation

206 The convection heating system in the climate chambers (inside/outside) consists of a hot gun in
207 an insulated enclosure. The maximum power output of the hot gun is 1500 Watt. The temperature
208 of the outside climate chamber is also controlled with a PT100 in combination with an ENDA
209 ET1411 digital thermostat temperature controller. The radiation power system in the outside
210 climate chamber consists of nine PAR38 light bulbs placed in front of the specimen which are
211 used to supply radiation energy, during summer measurements (Figure 3), which must simulate
212 the radiation. Three PAR30 light bulbs were used during summer and winter measurements to
213 serve as daylight and to ensure that metabolism and photosynthesis processes could continue
214 during the measurements.

215

216 Data acquisition

217 For the thermal data acquisition four calibrated “Advantech 4781” USB modules are used to read
218 the thermocouples. The data acquisition for the humidity sensors is done by a multifunctional
219 DAQ NI USB-6211 module.

220

221 Thermocouple measurements

222 All used thermocouples are of type T (Cu-Ni) with a diameter of 0.25 mm. Two PT100 are used to
223 measure the temperature in the outside climate chamber and in the guard section. Near the
224 PT100 a thermocouple was placed to verify the temperature in the outside climate chamber. Each
225 thermocouple measurement consists of two measurements on the same x-axis but on a different
226 height (y-axis) (figure 3, shown by the dotted lines).

227

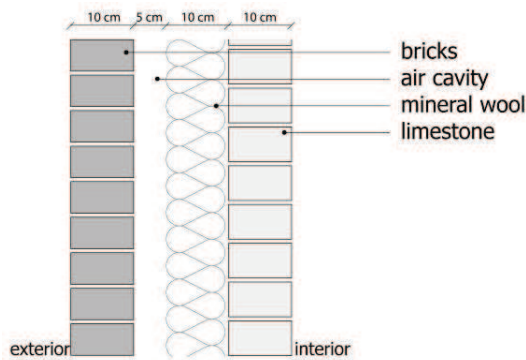
228 The temperature inside the canopy of the tested vertical greening systems is measured by
229 placing thermocouples on the backside of the leaves with thin transparent tape.

230

231 Specimen/sample mounting

232 The reference cavity wall consists of an inner wall of 100 mm thickness (limestone), mineral
233 insulation material of 100 mm thickness (Rockwool), cavity of 50 mm thickness and an outer wall
234 of 100 mm thickness (brick), (figure 5).

235



236

237 Figure 5 cross section of the reference cavity wall as used for the experiment.

238

239 **2.2 Theoretical calculations - thermal transfer coefficient**

240 For the thermal transfer coefficient the symbol U is used. The coefficient ($Wm^{-2}K^{-1}$) expresses the
 241 quantity of energy (W) passing through a material per area (m^2) and per temperature difference
 242 (K) between the two sides of the material. From thermal equilibrium theory it follows that:

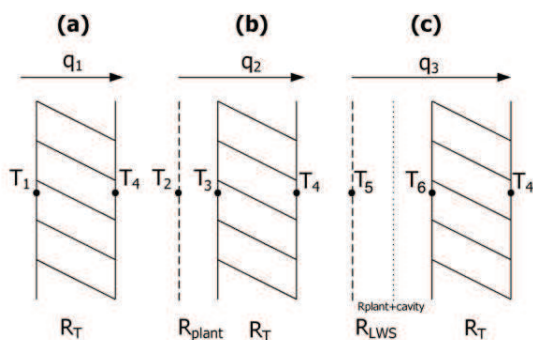
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244
$$U = \frac{Q}{A(T_i - T_e)} = 1/R \quad (1)$$

245

246 With Q the energy required for heating, A the area of the specimen, T_i the temperature of the
 247 inside chamber and T_e the temperature of the outside chamber. The formula can be used under
 248 the conditions that the heat transfer through the specimen is stable and that there are no heat
 249 losses through the wall of the heating chamber. The extra insulation layer with heated cavity
 250 (same temperature as inside the outside chamber) ensures that there is no exchange of heat out
 251 of the chamber. The heat loss therefore can be neglected.

252



253

254

255 Figure 6 Variables used for calculating the heat flow through a bare façade (a), directly greened
 256 façade (b) and a façade covered with a LWS panel (c). The dotted line represents the air cavity
 257 between plants and wall and the dashed line the plants.

258

259 For steady state conditions, the rate of heat flow (q) per unit area through the building's fabric
260 with an R-value, an indoor surface temperature (T_4) and an outdoor surface temperature (T_1) is
261 given by equation (2).

$$262 \quad q_1 = \frac{(T_1 - T_4)}{R_T} \quad (\text{W m}^{-2}) \quad (2)$$

263

264 Where T_1 (K) is the external surface temperature, T_4 (K) is the internal surface temperature, R_T
265 ($\text{m}^2 \cdot \text{K} \cdot \text{W}^{-1}$) is the thermal resistance of the wall.

266

267 As for the direct greened façade can be found:

$$268 \quad q_2 = \frac{(T_2 - T_4)}{R_{plant} + R_T} = \frac{(T_2 - T_3)}{R_{plant}} + \frac{(T_3 - T_4)}{R_T} \quad (\text{W m}^{-2}) \quad (3)$$

269

270 Where q is the heat flow, T_2 (K) is the surface temperature of plants, T_3 (K) is the surface
271 temperature below plants and R_{plant} ($\text{m}^2 \cdot \text{K} \cdot \text{W}^{-1}$) the thermal resistance of the plant species. For a
272 façade covered with LWS panels can be found:

$$273 \quad q_3 = \frac{(T_5 - T_4)}{R_{LWS} + R_T} = \frac{(T_5 - T_6)}{R_{LWS}} + \frac{(T_6 - T_4)}{R_T} \quad (\text{W m}^{-2}) \quad (4)$$

274

275 Where T_5 (K) is the surface temperature of the living wall system, T_6 (K) is the surface
276 temperature below LWS and R_{LWS} ($\text{m}^2 \cdot \text{K} \cdot \text{W}^{-1}$) the thermal resistance of the LWS.

277

278 Via expression (2) one can derive the thermal resistance of the plant layer for a direct greened
279 façade (eq. 3). The same can be found for the thermal resistance of a façade covered with a LWS
280 concept (eq.4):

281

$$282 \quad R_{PLANT} = R_T \frac{(T_2 - T_3)}{(T_3 - T_4)} \quad (\text{m}^2 \cdot \text{K} \cdot \text{W}^{-1}) \quad (5)$$

283

$$284 \quad R_{LWS} = R_T \frac{(T_5 - T_6)}{(T_6 - T_4)} \quad (\text{m}^2 \cdot \text{K} \cdot \text{W}^{-1}) \quad (6)$$

285

286 In order to calculate the overall thermal resistance of the reference cavity wall and the vertical
287 green systems analysed the material properties are used as given by the product information
288 sheets of the used materials in this experiment (Table 2). Besides it was used to compare the
289 theoretical calculations with the retrieved measuring data from the experimental set up. The
290 theoretical temperature line is for this purpose as well plotted in figures 7-12. The question mark
291 in table 2 represents the experimentally value to determined for thermal resistance of a vertical
292 green system in the presented research.

293

294 Table 2 cavity wall + vertical greening systems layers and related thermal resistance and
 295 conductivity.

Nr.	Layers of the construction	Thickness d [m]	Thermal conductivity λ [W/(m·K)]	Thermal resistance construction $R_c=d/\lambda$ [(m ² ·K)/W]
0	Vegetation layer	0.1-0.2		?
1	<i>external surface resistance</i>			0.04
2	masonry (clay)	0.1	1.00	0.10
3	Cavity	0.05		0.17
4	insulation material (mineral wool)	0.1	0.035	2.85
5	masonry (lime stone)	0.1	1.00	0.10
6	<i>internal surface resistance</i>			0.013
Total		0.45-0.55		3.27 + ?

296

297 **3. Results and discussion**

298

299 3.1 Direct façade greening

300 For the direct greening principle it is found that for the summer condition the average temperature
 301 of the wall surface ($T_{\text{ext wall surface}}$) is lower compared to the bare wall. The difference of
 302 temperature is reaching 1.7°C after 8 hours of heating. The insulation material inside the bare
 303 wall moderates the prevailing temperature difference between the outside and inside climate
 304 chamber, resulting in no temperature difference for the inside climate chamber (figure 7). The
 305 winter measurement after 72 hours shows that the wall surface covered directly with *Hedera helix*
 306 is warmer compared to the bare wall, with a temperature difference of 1.7°C. The air temperature
 307 of the inside climate chamber is lowered with 0.7°C in the case of the bare wall, which means that
 308 the vegetation layer slows down the rate of heat flow through the façade, resulting in an improved
 309 *R-value* of the system compared to the bare façade (figure 8).

310

311 3.2. Living wall system based on planter boxes

312 For the planter boxes system (LWS), it was found that for the summer condition the average
 313 temperature of the wall surface is lower compared to the bare wall, with a temperature difference
 314 reaching 8.4°C after 8 hours of heating (figure 9). This is a substantial difference with the direct
 315 greening system. Also for the living wall system based on planter boxes it was noticed that the
 316 insulation material inside the bare wall moderate the prevailing temperature difference between
 317 the outside and inside climate chamber, resulting in no temperature difference for the interior
 318 climate chamber. It is noteworthy to mention that the temperature difference between the air of
 319 the exterior chamber and the temperature of the extra created air cavity between LWS and

320 façade is 8.6°C. It was noticed that the humidity inside the exterior climate chamber lays between
 321 85% and 100% for the measurement; this is probably related to the moisture content of the
 322 substrates used for the living wall systems.

323 The winter measurement shows after 72 hours a temperature difference between the surface of
 324 the bare wall and the wall covered with planter boxes of 10.6°C, with a temperature difference
 325 between the exterior air temperature and the extra created cavity of 5.5°C. The interior air
 326 temperature difference after the measurement came up 2.1°C and thus resulting in an improved
 327 *R-value* of the system compared to the bare façade (figure 10).

328

329 3.3. Living wall system based on mineral wool

330 For the living wall system based on mineral wool (LWS), it was found that for the summer
 331 condition the average temperature of the wall surface is lower compared to the bare wall, with a
 332 temperature difference reaching 5.9°C after 8 hours of heating (figure 11). The air temperature
 333 difference between the exterior chamber and the air temperature of the extra created air cavity
 334 between LWS and façade was 5.9°C.

335 The winter measurement show a temperature difference after 72 hours between the surface of
 336 the bare wall and the wall covered with planter boxes of 10.6°C, with a temperature difference
 337 between the exterior air temperature and the extra created cavity of 4.6°C. The interior chamber
 338 air temperature difference after 72 hours came up 2.1°C and thus resulting also in an improved
 339 *R-value* of the system compared to the bare façade (figure 12).

340

341 Table 3. Summer season, temperatures recorded for 8 hours based on steady state situation.

Systems analysed	measuring points summer temperature (°C)				
	T _{ext}	T _{foliage}	T _{ext. wall surface}	T _{int. surface (outside)}	T _{int.}
bare wall	34.8	--	T ₁ ; 32.6	T ₄ ; 24.3	24.1
(a) direct green façade	34.1	T ₂ ; 31.4	T ₃ ; 31.0	T ₄ ; 23.9	24.0
(b) living wall system based on planter boxes	31.8	T ₅ ; 29.4	T ₆ ; 24.2	T ₄ ; 23.4	23.1
(c) living wall system based on mineral wool	34.8	T ₅ ; 30.4	T ₆ ; 26.8	T ₄ ; 24.7	24.4

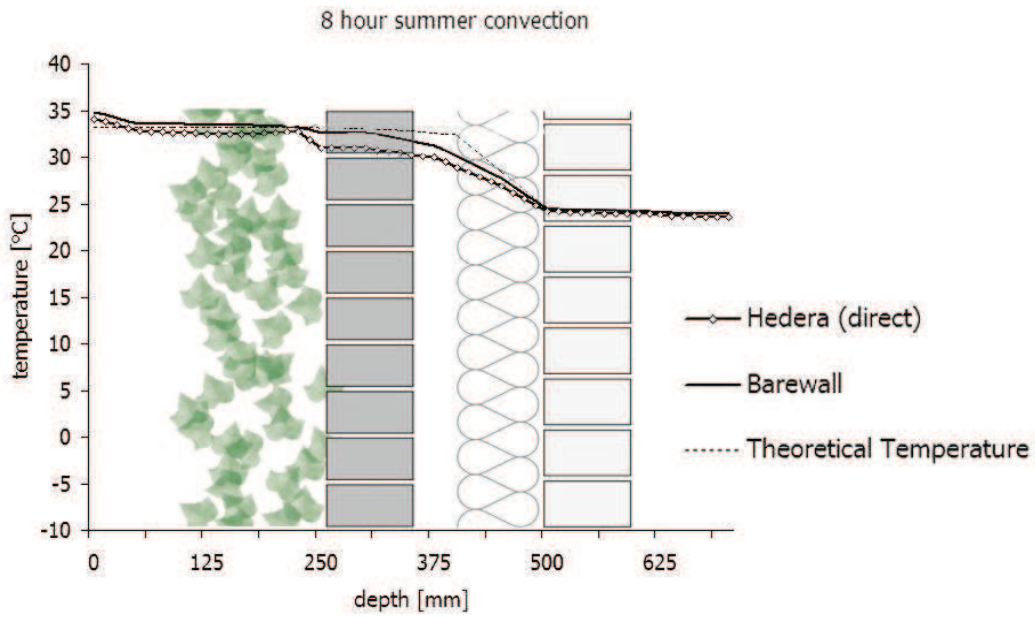
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344 Table 4, Winter season, temperatures recorded for 72 hours based on steady state situation

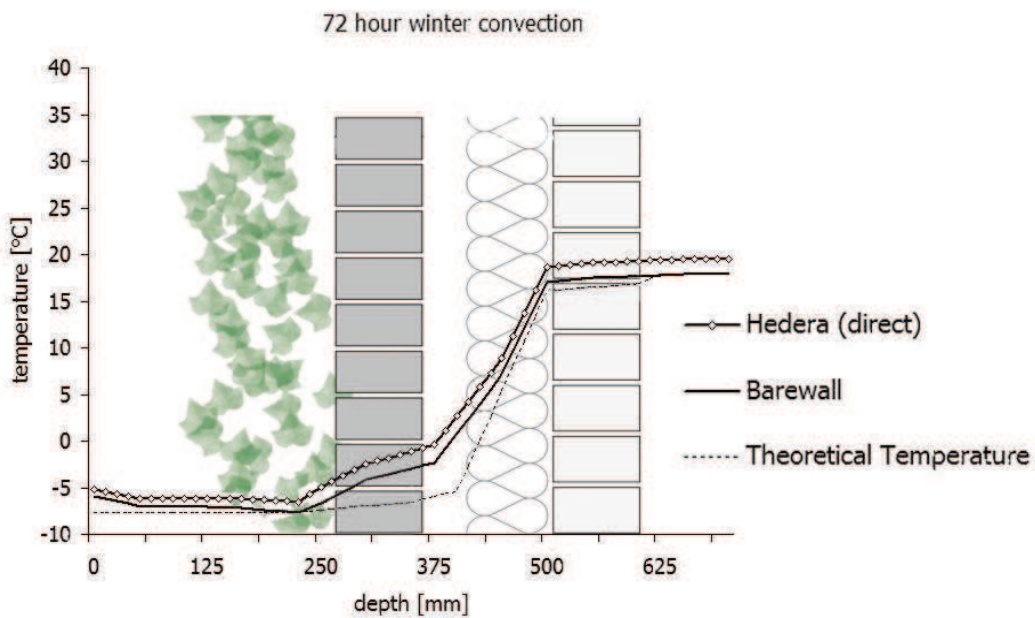
Systems analysed	measuring points winter temperature (°C)				
	T _{ext}	T _{foliage}	T _{ext. wall surface}	T _{int. surface (outside)}	T _{int.}
bare wall	-7.6	--	T ₁ ; -6.6	T ₄ ; 17.7	17.9
(a) direct green façade	-6.2	T ₂ ; -6.4	T ₃ ; -5.0	T ₄ ; 19.2	19.9
(b) living wall system based on planter boxes	-1.2	T ₅ ; -2.1	T ₆ ; 4.0	T ₄ ; 20.0	20.1
(c) living wall system	-2.1	T ₅ ; -3.0	T ₆ ; 4.0	T ₄ ; 20.1	20.0

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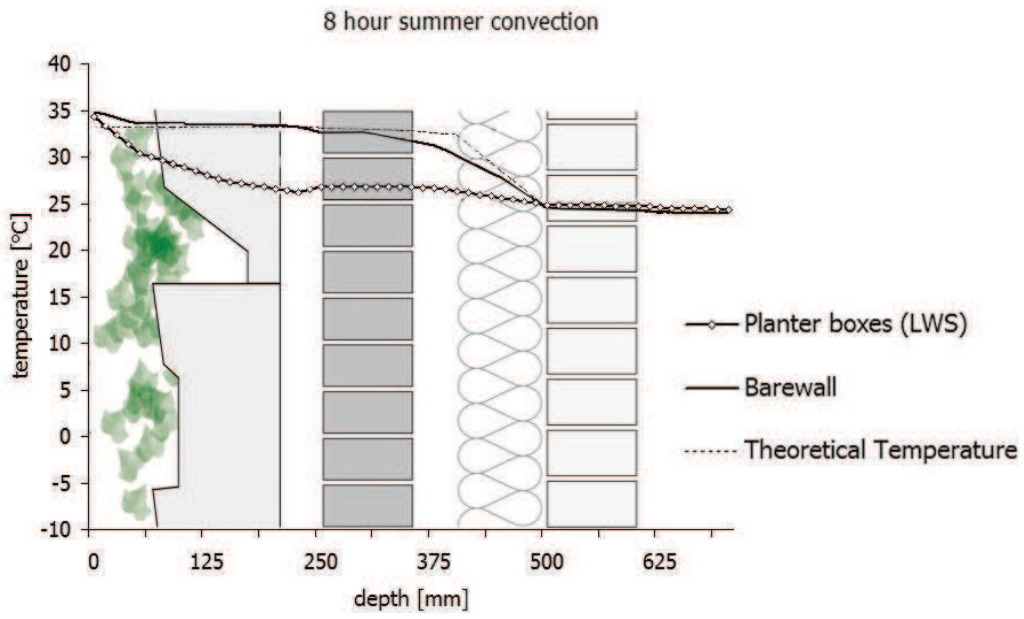
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Figure 7 direct green façade – 8 hours summer convection



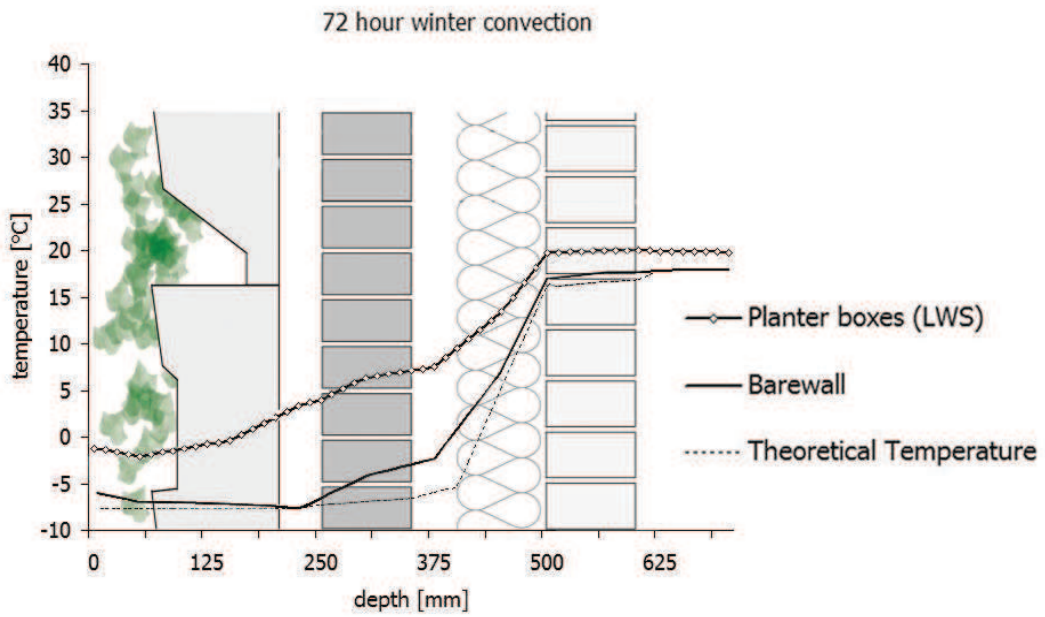
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Figure 8 direct green façade – 72 hours winter convection



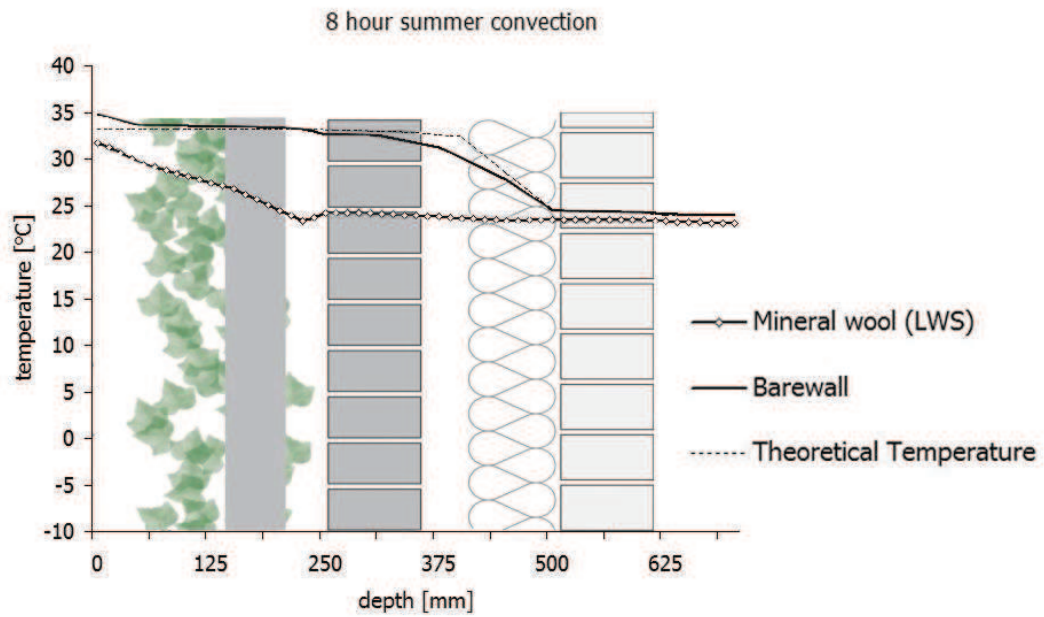
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Figure 9 LWS based on planter boxes – 8 hours summer convection



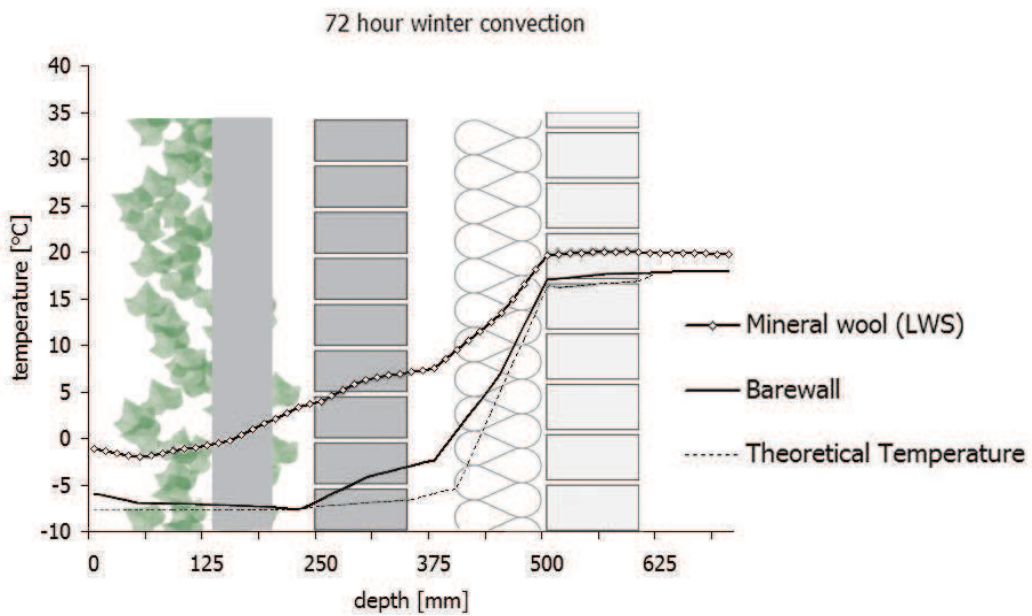
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Figure 10 LWS based on planter boxes – 72 hours winter convection



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Figure 11 LWS based on mineral wool – 8 hours summer convection



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Figure 12 LWS based on mineral wool – 72 hours winter convection

3.4 Calculation of thermal resistances and critical analysis of the obtained data

364 The conducted experiment allows estimating the thermal resistance of the vertical greening
 365 systems, according to paragraph 2.2. The calculation of equivalent R-values is based on the data
 366 collected in the experimental climate chamber, in particular on the measured interior and exterior
 367 surface temperatures, both for a summer and winter situation (Tables 5-6). For steady state
 368 conditions, the rate of heat flow per unit area through the direct greened façade can be estimated
 369 according to equations 3 and 5. For the living wall concepts equations 4 and 6 are used.

370
 371 Table 5 Estimated R-values for the greening systems tested under summer condition; assuming a
 372 steady state situation after 8 hours of heating. The values regarding the living wall systems must
 373 be considered as not reliable due to the unexpected high value(s).

Summarized thermal resistances summer measurement	
<i>Vertical greening systems</i>	<i>R-value (m²·K·W⁻¹)</i>
Bare wall	3.43
<i>Hedera helix</i> direct	0.66
LWS based on planter boxes	12.81
LWS based on mineral wool	33.15

375
 376 **Table 6 Estimated R-values for the greening systems tested under winter condition;**
 377 **assuming a steady state situation after 72 hours of cooling.**

Summarized thermal resistances winter measurement	
<i>Vertical greening systems</i>	<i>R-value (m²·K·W⁻¹)</i>
Bare wall	3.42
<i>Hedera helix</i> direct	0.18
LWS based on planter boxes	1.30
LWS based on mineral wool	1.10

379

380 The R-values values calculated for the summer measurement (Table 5) are extremely high. This
381 is probably related to insufficient measuring time (8 hours) to reach a steady state situation for the
382 heat flow through the vertical greening systems, in particular for the living wall systems analysed,
383 due to the high temperature differences between the several layers (vegetation, materials, air,
384 etc.) involved. The temperature gradient ΔT_{lws} (difference between T_1 and T_2) has a high
385 influence on the outcome of the equation used (eq. 6). The larger the temperature drop over the
386 living wall system, the higher the R_{LWS} value will be. In the case of the summer measurements
387 after 8 hours heating, high temperature gradient (T_1-T_3 up to 10°C) over the living wall systems
388 was found as earlier described (see also figures 10 and 12), whereas the temperature gradient
389 over the bare wall (T_3-T_4) appeared to be 1.5°C as a maximum. Noteworthy to mention is the
390 striking temperature drop found for the LWS systems under summer conditions between the
391 supporting material and substrate and façade (figures 10 and 12). The reason for this could be
392 because of the evaporative cooling capacity of the composite system, however further research is
393 needed to really understand this mechanism.

394 Worth mentioning; the real effect of the moisture content (evapotranspiration; the contribution of
395 vegetation and substrate) on the heat transfer mechanism is inside a closed and sealed
396 environment should be further investigated. In fact, also the evaporation and the water (vapour)
397 trapped inside the chambers plays a role. It is likely that this mechanism causes the high
398 temperature differences found for the summer measurement. Building materials (abiotic) are
399 tested via the same principle (steady state) according to the standard NEN-EN 1934, the
400 difference with the executed experiment is the introduction of a (unknown) biological factor. In
401 practice the (exterior climate chamber) humidity levels are affected due to ventilation by wind.
402 Interior humidity levels are mostly influenced by the use of a building (human activity, cooking,
403 etc.).

404

405 *R-values* deriving from winter measurement, presented in table 6, are lower compared to the
406 ones derived from summer measurements. This is related to the measuring time of 72 hours
407 which tends to be really steady state. Another important aspect is the evaporative character of the
408 vertical greening systems under colder temperatures (frost) which is less compared to the
409 summer measurement were the plants (+substrate) are constantly (evapo)transpiring to fulfil
410 their biological functions (metabolism). Again it is observed that the greening systems positively
411 influence the temperature development through the façade. This still indicates that the thermal
412 resistance of the construction is improved by adding a green layer.

413

414 **Conclusion**

415 The present research allows studying the thermal behaviour during summer and winter seasons
416 of different vertical greening systems under boundary conditions. From the summer

417 measurements a considerable effect in reducing the temperature development in the exterior
418 masonry by applying vertical greening systems can be noticed, in particular for the living wall
419 systems analysed. This means that less accumulation will occur in a greened façade, resulting in
420 less heat radiation at night. Such effect results in energy saving for air conditioning and also in a
421 possible reduction of urban heat island effect. It can also be noticed that the greening systems
422 influence positively the temperature development through the façade, resulting in an improvement
423 of the thermal resistance of the construction.

424 The results obtained show that the experimental set-up (climate chamber “hotbox”) acts
425 wherefore it was designed, as from a building physics point of view positive temperature
426 differences were found between the bare wall and the different vertical greening systems
427 attached to the same bare wall configuration.

428

429 The main conclusions that can be drawn from the presented results are the following:

430

- 431 - For all the cases analysed it was noticed that the insulation material inside the bare wall
432 moderates the prevailing temperature difference between the outside and inside climate
433 chamber, resulting in no temperature difference for the interior climate chamber for
434 summer conditions in this comparative study. However vertical greening system reduce
435 outdoor temperature resulting in urban heat island mitigation.
- 436 - Temperature differences can be found between the bare wall and vertical greening
437 systems that were attached to the same bare wall.
- 438 - The direct façade greening intercepts the solar radiation as shown by the temperature
439 difference of 1.7°C after 8 hours of heating for summer conditions; for winter conditions
440 warmer temperatures are found due to the presence of *Hedera helix*, which means that
441 the vegetation layer slows down the rate of heat flow through the façade, resulting in an
442 improved *R-value* of the system compared to the initial bare supporting wall.
- 443 - The results related to the living wall system based on planter boxes show a temperature
444 difference reaching 8.4°C after 8 hours of heating compared to the bare wall; for the
445 winter measurement the interior air temperature difference after the measurement came
446 up 2.1°C and thus resulting in an improved *R-value* of the system compared to the initial
447 bare supporting wall.
- 448 - The living wall system based on mineral wool is the most effective with regard to summer
449 cooling with a temperature difference reaching 5.8°C after 8 hours of heating compared
450 to the bare wall. For the winter measurements a similar trend compared to the living wall
451 system based on planter boxes was noticed (i.e. the interior chamber air temperature
452 difference after 72 hours came up 2.1°C), resulting in an improved *R-value* of the system
453 compared to the initial bare supporting wall.

454

455 This research gives insight in the positive influence of green systems on the thermal behaviour of
456 buildings. Starting from the measurements, an estimation of R-values is provided. In order to
457 obtain more realistic results regarding the *R-value* of greening systems, reaching a steady state
458 situation (with a measuring form more than 8 hours) and improving of the climate chamber is
459 needed. In fact, enlarging the volume of the exterior chamber (i.e. where the greenery is placed)
460 could lower the influence of evaporation. Additional research is required for an accurate thermal
461 resistance calculation.

462

463

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469

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