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A *Hedera* green façade – Energy performance and saving under different maritime-temperate, winter weather conditions

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ABSTRACT

Thermal regulation is a key ecosystem service provided by urban plants. In addition to summer cooling, plants can insulate buildings against heat loss in winter. Research was conducted over two winters using replicated small-scale physical models to simulate heat loss from a built structure and to investigate the insulation properties of plants during cold weather. Brick cuboids were constructed around a water tank maintained at 16 °C and energy use monitored. Covering cuboids with ivy (*Hedera helix*) reduced mean energy consumption by 21% compared to bare cuboids during the first winter (means of 4.3 and 5.4 kWh per week, respectively). During the second winter, when foliage was more extensive a 37% mean saving was achieved (3.7 compared to 5.9 kWh per week). The presence of *Hedera* enhanced brick temperatures significantly compared to bare walls. Temperature differences were affected by weather parameters, aspect, diurnal time and canopy density. Largest savings in energy due to vegetation were associated with more extreme weather, such as cold temperatures, strong wind or rain. Under such scenarios green façades could increase energy efficiency by 40–50% and enhance wall surface temperatures by 3 °C. These empirical studies with replicated treatments augment previous research based on urban modelling and data from non-replicated individual buildings *in situ*. They indicate that planting design requires more attention to ensure the heat saving aspects associated with green façades and shelter belts are optimised. These aspects are discussed within the context of wider urban ecosystem services provided by vegetation, and implications for climate change mitigation.

1. Introduction

Energy demand in temperate climates is a key sustainability issue [1]. In developed countries 20–40% of total energy is consumed in buildings [2] and the built environment accounts for >50% of all UK carbon emissions [3] with extensive economic and climate change implications [1]. Green façades/walls and roofs have been the subject of significant attention over recent years partly due to their wider role in urban heat island mitigation [4,5], but also their ability to shield buildings from excessive solar gain and cool via evapo-transpiration [6]. This dual cooling can significantly reduce temperatures around the building envelope and hence decrease energy demand for mechanised cooling [7].

Vegetation can also ameliorate winter effects on a building, and in turn reduce heat energy consumption; although this has received comparatively less attention [8]. The premise has been explored over three decades [9–11]. There remains a lack of research with replicated treatments under field conditions, however, particularly with respect to maritime-temperate climates such as the UK. Most previous studies have been dominated by continental climatic pressures e.g. central/eastern parts of the contiguous USA. Inferences from such research to temperate scenarios are problematic, not least due to typically milder winters, variation in sunlight hours (cloud cover) and solar azimuth angle (hence radiation intensity). Yet, there is an urgent need for innovative and practical options which address the poor energy performance of much of the housing stock in countries such as the UK and Eire. In the UK, 80% of housing was built prior to 1980, with little focus on energy efficiency in construction [12]. Despite being a 'temperate' climate, the UK has one of Europe's highest rates of winter mortality [13] with 23,500 excess deaths in winter 2003/4 [14].

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Nomenclature

ANOVA	analysis of variance
df	degrees of freedom
h	time [hours]
k	thermal conductivity [W m^{-1} K^{-1}]
$kgCO_2^e$	kg carbon dioxide equivalent green-house gas
lbh	length, breadth, height
LSD	least significant difference
N	north aspect
n	number of replicates
P	probability, lower values represent greater confidence
PC	planted cuboid
S	south aspect
UC	un-planted cuboid
U10	wind speed at 10 m height
v	versus
w/c	week commencing

Wind chill and infiltration of cold air (with the associated convective losses) are the most significant factors in the poor energy performance of old housing stock [7,9,15]. Infiltration of cold air is undesirable not only due to temperature reduction in the building envelope, but also cold air meeting warm causes water vapor to condense, particularly in cavity spaces. Vegetation covering a building can reduce wind velocity through the surface resistance of the canopy, and thus reduce both cold air infiltration and convective heat loss to a building [7,9,10], and in turn reduce carbon consumed in heating the home or office [16]. These thermal benefits are augmented by a spectrum of well-documented additional benefits within the anthrosphere, not least habitat provision for urban biota [17], intercepting precipitation and reducing run-off rates [18], screening out aerial particulate matter and improving air quality [19], contributing to psychological well-being and improving the aesthetics of the cityscape [20,21].

For decades it has been understood that hedges and trees reduce wind-chill to surrounding structures or landforms by providing a wind break; although much of the focus has related to crop or livestock protection within agriculture e.g. [22]. Some authors have applied these principals to vegetated walls noting a reduction in draughts surrounding apertures, (and hence air flow into/out of a building), together with warmer air retained against the building envelope [23]. Indeed, Dewalle and Heisler [24] suggest that vegetation can reduce cold air infiltration to the building envelope by up to 40%. Subsequently, Heisler [25] predicted through modelling that well-designed shelter-belt planting could result in heat energy savings of 10–25%. Liu and Harris [11] were able to demonstrate that the addition of shelterbelt trees around office buildings in Scotland, UK, reduced convective heat losses, resulting in energy savings of 8%. In addition to the canopy providing aerodynamic resistance, vegetation can also protect masonry from freeze/thaw, and infiltration of damp following precipitation by forming a physical barrier. Species such as *Hedera helix* present a multi-layered surface, which aids run off and can stop moisture reaching the wall [26].

Physical and geographical features of the building will also influence efficacy, including orientation, prevailing weather, and thermal characteristics of the masonry, coupled with architectural aspects such as the volume, dimensions, and geometry of the walls and surrounding structures [27,28]. Such physical characteristics create flux in the microclimate close to a heated wall due to convection and conduction, with factors such as wind-eddy, albedo, humidity, and shade/solar gain creating a dynamic zone of 'thermal mixing' adjacent to the wall surface; all of which are influenced by the addition of vegetation [29]. Building occupancy has a significant effect on heat energy consumption altering demand for heating due to variation in the thermal gradient (e.g. care homes require higher temperatures than shops), but also heat loss through factors such use of entry and exit points [30].

In an attempt to minimise the variations encountered in 'real' buildings, the work reported here used replicated, heated brick cuboids. The cuboids were constructed with a single layer of brick, analogous to the walls of brick terrace houses typical of inner-city housing stock in UK cities. The 'cuboids' were not intended to mimic a 'real' house, just provide an experimental basis to evaluate the concept of vegetation used as thermal insulation. Our use of replicated cuboids outdoors were unlikely to fully represent the thermal properties and aero-dynamics around buildings *in vivo* but a number of the approaches adopted were considered advantageous in attempting to reduce bias associated with individual buildings and associated micro-climates (e.g. uniform, replicated structures located within a small area). Indeed, Hunter et al. [31] have recently criticised studies on green walls due to research design problems; with the small number of experimental studies lacking replication, providing insufficient information about the microclimate parameters measured, and assumptions through modelling studies not always delineated or justified. As such the replicated, empirical-data gathering approach was adopted here.

The research utilised a green façade system rather than a living wall. Green façades comprise of plants in the ground (or in pots), and grown up the side of a building, either attaching themselves directly or trained up a trellis/framework placed against the wall. The green façade was chosen to exploit a simple design that readily translates into practice, and to minimise nutrient, water and energy costs associated with some living wall systems [32]. *H. helix* was selected as it represents a commonly-used garden or landscape plant, often found growing up domestic properties either after intentional planting or self seeding.

The aim of this research was to explore if vegetation can play a role in insulating a wall in a maritime-temperate climate. Through replication, and monitoring heat loss over two UK winters, our objectives were to quantify potential energy and carbon savings; whilst also evaluating the relative effectiveness of vegetation against different winter weather phenomena. The kWh savings and carbon savings are both quantified; however, no attempt has been made to review the embodied carbon in plant provenance, or indirect carbon consumed in plant maintenance *in situ*.

The numerous potential benefits for retro-fitting scenarios in older housing stock [33,34] validate the importance of this work. Despite climate change increasing global heating, north-west Europe may experience wetter and colder winters due to the weakening of the Atlantic meridional overturning circulation (AMOC); with severe weather events increasing in both frequency and magnitude [35].

2. Materials and methods

Brick cuboids were laid out in a matrix design with 12 used in the first (4 Jan.–31 Mar. 2010) and an additional 8 (i.e. 20 in total) in the second (1 Dec. 2010–30 Mar. 2011) experimental phase (Fig. 1). Cuboids were constructed outdoors in a field site at the University of Reading, Reading, UK, using a standard red clay housing brick (classified BSEN 771, Class B, 215 × 103 × 65 mm lbh; thermal properties: $k = 1.1$ Wm^{-1} k^{-1}, Blockley's Brick Holdings PLC, Telford, UK). A single skin of bricks was placed on a grey concrete slab footing (682 × 500 × 40 mm lbh) and a 'damp course' layer (polypropylene tape 1.05 mm thick) was incorporated above the

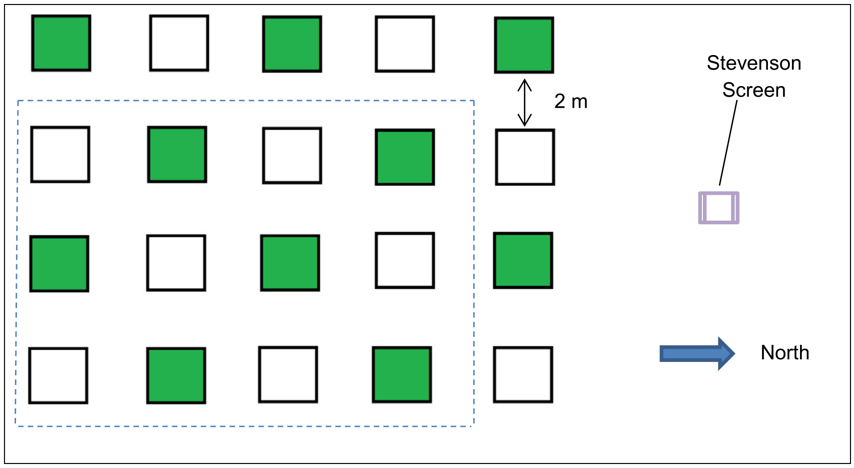

Fig. 1. Final cuboid layout with shaded cuboids planted with *Hedera helix* and open cuboids un-planted. Area within dashed line represents the original 12 cuboids, but extra cuboids were added to increase replication in phase 2 and help further reduce location bias.

basal layer (Fig. 2). The bricks were stacked in a stretcher-bond with a slab 'roof'; total volume: 0.25 m^3 (0.6 × 0.6 × 0.7 m lbh) and each cuboid placed 2 m apart. The bricks were not mortared but were orientated to avoid any obvious air gaps between adjacent bricks. An aluminium foil-coated, plastic air-filled sheet ('foil bubble-wrap') was placed on the top and base of each cuboid; hence 'walls' were the principal route for heat migration. A sealed 25 l opaque polypropylene container was placed inside, filled with potable water. A calibrated Protx 1020, 75 W thermostatic heater (AquaCare Inc., Gurnee, Illinois, USA) maintained internal water temperature at 16 ± 0.5 °C. Heaters were connected to mains electricity via a Maplin N67HH power consumption monitor (Maplin Electronics, Rotherham, UK); this measured kWh consumed (accurate to 0.5%). Power monitors were checked by recording power consumed over 1 h i.e. 75 W. Equivalent carbon consumed was calculated using the UK Government Defra/DECC conversion factors [36], which correlates 1 kWh–0.48357 kg carbon dioxide equivalent ($kgCO_2^e$). This conversion accounts for UK generated, imported energy and grid losses via the UK National Electricity Grid.

Half the cuboids were planted (PC) with *H. helix*, two plants per side i.e. eight plants per cuboid. Plant stems were fixed in place with fine galvanised steel wires looped over the cuboids and the developing shoots trained up these (at approximately 20 mm from the wall) to stop wind dislodging the stems. Control cuboids were left un-planted (UC) but with wires in place to ensure the only difference between treatments was the presence of plant material. *Hedera* were supplied as two year old stock in 2 l pots with foliage dimensions approximately: 0.4 × 0.1 × 0.8 (lbh). During the first winter phase, *Hedera* foliage covered approximately 80% of the PC to a depth of 30–60 mm (1–2 leaves deep), with longer stems trained over the cuboid 'roofs'. Power was recorded daily at 10.00 h. By the following winter (2010/11) foliage had completely covered the 'roof' and walls to a depth of 60–80 mm (5–7 leaves deep).

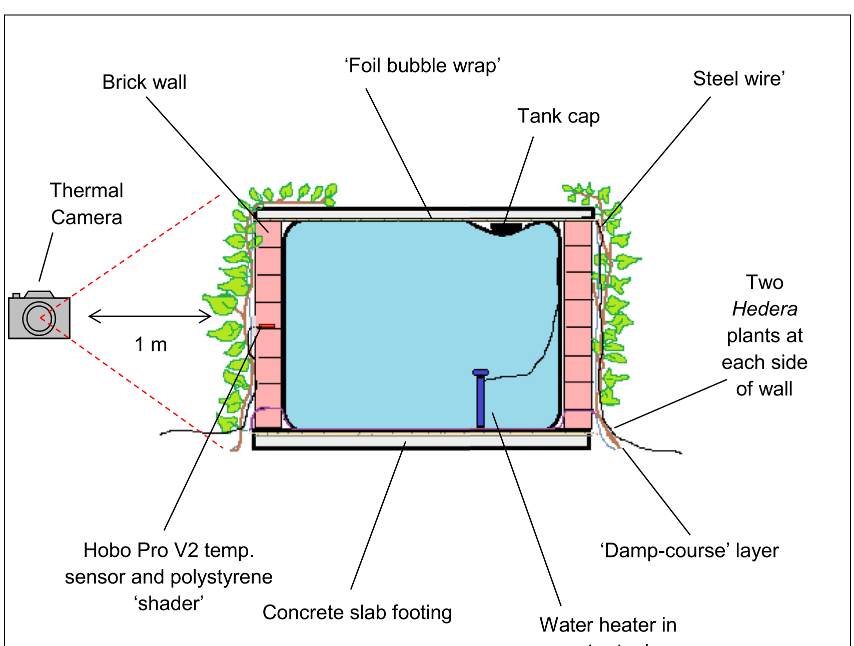

Fig. 2. Cross section of planted cuboid showing position of heated polypropylene water tank and temperature sensor.

Ambient air temperature was logged every 10 min. Temperature sensors (Hobo Pro V2 external temperature sensors, Tempcon Instruments Ltd. Arundel, UK) were located in a Stevenson screen, 0.7 m from the ground (i.e. the same height as the cuboids), on the northern edge of the experimental site. Brick and foliage temperatures were recorded at specified times under different weather conditions using a Thermal Image Camera (NEC Thermo Tracer TH7800, NEC infra-red technologies Ltd., Tokyo, Japan; −20 to 250 °C range with 0.2 °C resolution [at 8–14 μm]), Surface temperatures of walls or foliage were derived from thermal images of each wall on every cuboid. Mean temperature for each aspect/cuboid/time was derived from a random sample of 20 data points spread across each thermal image. Treatment effects on wall temperature were generated from these mean values via an analysis of variance (ANOVA) (Genstat:13 software, Rothamstead Research, Harpenden, Hertfordshire, UK). In addition to thermal images, temperature recording of the brick walls (every 10 min) was implemented from 20 Jan. 2011 in order to assess diurnal variation. Small apertures (7 mm wide) were made between two bricks and Hobo Pro V2 sensors inserted with the tip of the sensor approximately 10 mm from the wall exterior surface. Gaps were sealed with an adhesive putty (blu-tack). Sensors were located centrally on the southern exterior of the cuboid (0.5 m from ground and 0.2 m from roof). A 60 mm square of polystyrene backed aluminium-foil was used to shade sensors from direct solar radiation. Temperature sensors were accurate to ±0.2 °C and calibrated every 3 weeks. Temperature data were collated into four 'key' times during the daily cycle: 3.00, 9.00, 15.00, 21.00 h with mean values being generated from the readings 20 min prior, at and 20 min after each key time; these mean values for each cuboid being using in subsequent ANOVA.

The University of Reading, located in central southern England (Latitude 51.4429602554, Longitude −0.9540650288), experiences a mean minimum winter temperatures of 1 °C and mean winter high temperature of 9 °C (Dec.–Feb.) with on average 54 mm rainfall per winter month, with precipitation falling on average 18 days out of each month. During the period discussed, however, the winters were atypically severe and cold; both winters falling within the five coldest winters experienced over the previous 35 years. Snow was observed in both winters, with drifts of 300–400 mm recorded in Jan 2010, accompanied with sub-zero nocturnal temperatures during the entire month. Rainfall was above average in Feb. 2010 and Feb. 2011. Meteorological data were obtained from the University's primary weather station, located approximately 200 m from the experimental site, with the anemometer 10 m above ground level (*U10*). This information was used to define a range of climatic conditions (Table 1), which in turn were used to denote the prevalent weather conditions for each week (examples being given in Table 2). Prevalent weather conditions being defined as those that dominated each day, and did so on at least five days out of every seven within the one calendar week. Energy consumption data is depicted on a calendar week basis and compared against the prevalent weather conditions for that week.

Depicting data in this manner provided a useful compromise to illustrate trends for any one type of weather pattern, but could mask the influence of more discrete weather events that may occur within an individual week. In an attempt to analyse the effects of more consistent weather patterns, energy use data per day was also calculated and presented for different weather conditions.

Analysis of variance (ANOVA) was implemented and took account of any unbalanced design and ensured variance in the data was homogenously distributed. Mean values derived from ANOVA are presented, with the associated LSD ($P = 0.05$) value.

3. Results

3.1. Snow

Four weeks were identified where the weather was dominated by falling and lying snow. In each week, energy consumption was significantly higher with UC compared to PC (Fig. 3); the UC demonstrating some of the highest energy use through the entire experiment (approximately 7 kWh^{-1}). Even a partial cover of the cuboids by vegetation enhanced energy efficiency, by approximately 26% (e.g. 6 Jan., 2010, Fig. 3) but this could be further enhanced on occasions by full coverage (i.e. 29%, 22 Dec., 2010, Fig. 3). Pooling data for different weeks and comparing partial and full canopy cover, however, did not show an overall significant advantage of the increased foliage cover/thickness during snow periods; partial cover PC = 4.9 kWh and full cover PC = 5.0 kWh per cuboid; $P = 0.751$; LSD 0.39, df 35. Snow depth, however, also varied between the different periods (e.g. 6 Jan. 2010 max = 175 mm; 15 Dec. 2010 max = 13 mm) and this may also have affected the insulation dynamics. Physical differences in snow cover were evident too as ambient temperatures rose; snow was more likely to melt, and to melt more rapidly with the UC treatment compared to the PC (Fig. 4).

3.2. Freezing temperatures, wind and rain

The advantage of the PC was again evident during periods where temperatures were typically sub-zero and where wind and rain were common, but there was no snow fall *per se* (i.e. freezing periods without any 'insulation' effects of lying snow). Energy consumption was significantly reduced in PC (typically 4–5 kWh^{-1}) compared to UC (e.g. 6–7 kWh^{-1}) on all weeks evaluated under these conditions (Fig. 5). During Jan. 2011 PCs were typically 39–42% more efficient in energy use than their un-vegetated counterparts. Indeed, as plant growth during summer 2010 increased the canopy cover/density between consecutive winters, the differentials between the PC and UC tended to increase (i.e. compare relevant weekly data for winter 2010 and winter 2011; Fig. 5). In addition, the PCs when they had complete canopy cover consumed significantly less energy (4.17 kWh^{-1} in 2011) than when only partially covered in 2010 (4.87 kWh^{-1}; $P < 0.001$; LSD 0.34, df 46).

Observational differences were evident between UC and PC during periods of rainfall, with walls behind the foliage often being dry to touch, compared to surface moisture evident on UC walls. During these conditions, thermal images demonstrated that surface temperatures were also different e.g. 20 Jan 2010 at 15.30 – ambient temp. = 0.4 °C with mean wall temps of UC = 3.1 °C and PC mean foliage temp of 0.6 °C ($P < 0.001$; LSD 0.33, df 11), suggesting more thermal energy was being emitted from the UC.

3.3. Cold, wind and rain

Energy consumption patterns were similar to those of sub-zero condition in wind and rain, with significant advantages being evident with PC in terms of energy savings, especially at times when the foliage canopy was complete (Fig. 6). As before, walls behind the foliage often appeared visibly drier during wet periods.

3.4. Cold and wind

The advantage of the vegetated cuboids was again evident during episodes of windy weather where the weekly mean ambient temperature rose just above zero. (NB – Some periods in these weeks experienced overnight frosts, but rainfall and high solar

Table 1
Climatic definitions.

Minimum ambient temperature	Nomenclature	Mean daily t_{min} (°C) Weekly mean of daily t_{min} (°C)
Moderate	TM	T > 4.0
Cold	TC	T > 0.0 ≤ 4.0
Sub-zero	TSz	T ≤ 0.0
Wind force		Daily mean *U10* wind velocity (ms^{-1}) Weekly mean of daily max *U10* & max gusting (ms^{-1})
Calm	WC	<5.5 and gusting < 8.5
Wind	WW	≥5.5 and/or max gusting ≥ 8.5
Precipitation		Total daily/weekly depth/duration
Low rainfall	LR	<2 mm and <2.0 h
Moderate rainfall	MR	≥2.0 mm and/or ≥ 2.0 h
Snow (week)	S (W)	Total weekly depth (mm)
Solar radiation		Total daily/weekly h with solar radiation ≥ 120 Wm^{-2}
High winter solar irradiance (day)	High sun (D)	≥3.0 h
High winter solar irradiance (week)	High sun (W)	≥20 h
Low winter solar irradiance (day)	Low sun (D)	<3.0 h
Low winter solar irradiance (week)	Low sun (W)	<20 h

Table 2
Weekly weather designation and prevalent conditions.

Weather	Prevalent conditions	Abbreviations
Snow	Snow cover for ≥5 days	S
Freezing temp., wind and rain	Mean weekly temp. sub-zero, wind, moderate rainfall and low winter solar irradiance	TSz, WW, MR, low sun
Cold, wind and rain	Mean weekly temp. cold, wind, moderate rainfall and low winter solar irradiance	TC, WW, MR, low sun
Cold and wind	Mean weekly temp. cold, wind, low rainfall and low winter solar irradiance	TC, WW, LR, low sun
Cold, wind and sun	Mean weekly temp. cold, wind, low rainfall and high winter solar irradiance	TC, WW, LR, high sun
Moderate and sun	Mean weekly temp. moderate, wind, low rainfall and high winter solar irradiance	TM, WC, LR, high sun

radiation were rare). Although energy use was lower than in the snow or freezing/rain scenarios, PC could be as much as 43% more efficient than the equivalent UC, e.g. w/c 2 Feb., 2011 (Fig. 7).

Analysis of brick temperatures for w/c 2 Feb., reveals that on average the PC was 2.1 °C warmer than the UC ($P < 0.001$; LSD 0.50, df 335). Greatest differentials in brick surface temperature were apparent when ambient air temperatures were low. For example, when air temperatures overnight were sub-zero, e.g. 31 Jan, 2011, there was a 3.0 °C differential; brick surface temperatures PC = 3.9 °C and UC = 0.9 °C ($P < 0.001$; LSD 0.88, df 47), whereas during warmer nights differentials were smaller e.g. 2.4 °C on 2 Feb. 2011; PC = 6.0 °C and UC = 3.6 °C ($P < 0.001$; LSD 0.34, df 27). Plant canopies impeded the wind, with foliage directly adjacent to brickwork being inert even with external wind gusts >8.5 ms^{-2}, whereas leaves at the surface and edges were in constant motion at such wind velocities.

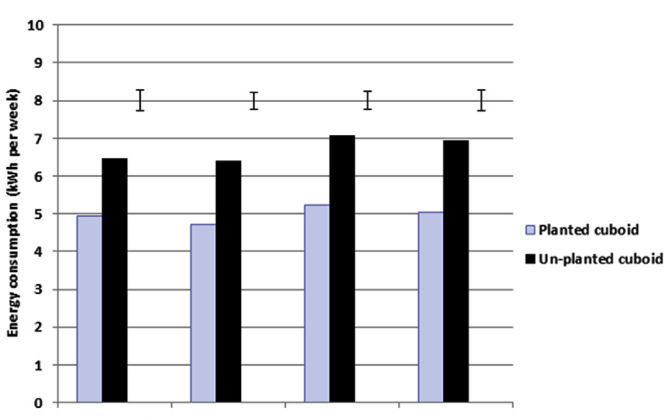

Fig. 3. Snow. Weekly energy consumption per cuboid, where weather was dominated by snow. Weeks with * represent periods where foliage cover was not complete. Bars = LSD; df = 11 for * weeks, and 19 for remainder. Data week commencing.

3.5. Cold, wind and sun

Energy consumption was generally lower under periods of relatively high solar irradiance, although air temperatures could still be cold e.g. in March of each year (Fig. 8). During Mar. 2010, when the vegetation canopy was still incomplete, differences between PC and UC were not always significantly different. In contrast, by Mar. 2011 when planted cuboids were fully covered with foliage, differentials between the two treatments were large (weeks commencing 2, 9 and 16 Mar. 2011, Fig. 8). In the w/c 9 Mar. 2011, the vegetation reduced energy use by almost 50% compared to UC. Indeed, when diurnal brick temperatures are compared the PC is a mean 1.6 °C warmer over the entire week ($P < 0.001$; LSD 0.65, df 335), with episodes of heavy over-night frosts resulting in occasions when the PC was 3.0 °C warmer than the UC (e.g. 9 Mar. 2011, brick temp. PC = 4.8 °C and UC = 1.8 °C; $P < 0.001$; LSD 1.05, df 27). More detailed analysis of the data for this period/weather conditions, however, indicated that opposite could also be true at other times, i.e. warmer temperatures associated with the UC treatment. For those data sets where ambient temperature above freezing was combined with >3 h consistent solar irradiance (e.g. early afternoon), temperatures of UC bricks could exceed those of PC bricks (e.g. 4 Mar. 2011, Fig. 9). After this peak, however, temperatures declined more rapidly in the UC than the PC treatment over the evening period.

3.6. Moderate temperatures and sun

During these relatively warm weeks (mid – late Mar. in both years), no significant advantage in energy consumption was

Fig. 4. Snow melt was more rapid around the base of unplanted cuboids (UC) left, compared to planted cuboids (PC) right. Images from 11 Jan 2010 at 15.00 h.

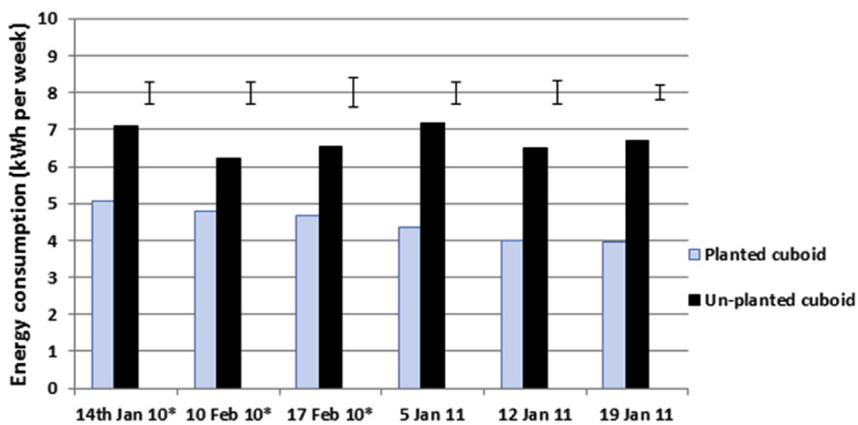

Fig. 5. Freezing, wind and rain. Weekly energy consumption per cuboid, where weekly mean ambient temperature was sub-zero, with wind, moderate rainfall and winter sun of <3 h. Weeks with * represent periods where foliage cover was not complete. Bars = LSD; df = 11 for * weeks, and 19 for remainder. Data week commencing.

evident with PC (Fig. 10). The duration of solar radiation was >30 h per week, with intensity frequently >250 Wm^{-2}. This coupled with the higher solar azimuth angle, contributes to the influence of solar irradiance reducing the thermal gradients between brick work and air, with short episodes in the afternoon when ambient air temperatures rose above 10 °C (see comments for key times below).

3.7. Energy consumption based on 24 h diurnal data sets

Restricting data to data sets associated with individual days confirmed that energy savings were evident with PC compared to UC across a range of weather scenarios (Fig. 11). Largest differentials between the treatments again being associated with more extreme

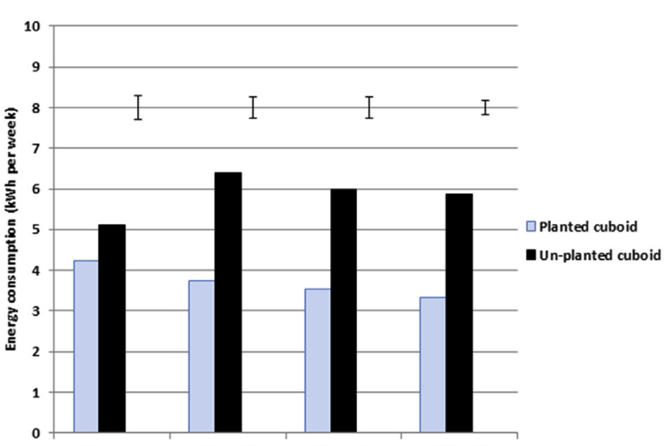

Fig. 6. Cold, wind and rain. Weekly energy consumption per cuboid, where weekly mean ambient temperature was cold, with wind, moderate rainfall, and winter sun of <3 h. Bars = LSD; df = 11 for * weeks and 19 for remainder. Data week commencing.

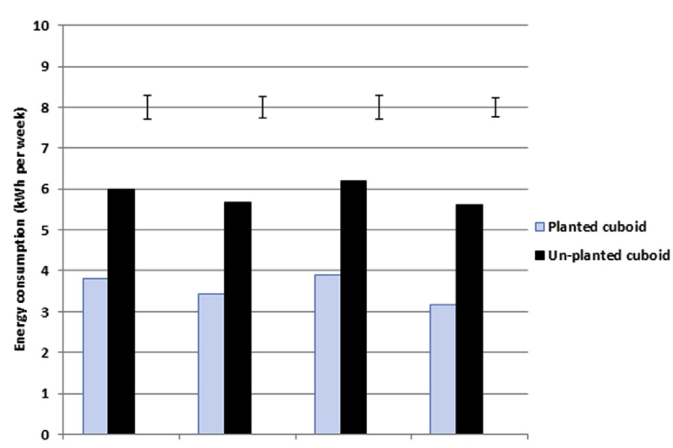

Fig. 7. Cold and wind. Weekly energy consumption per cuboid, where weekly mean ambient temperature was cold, with wind, low rainfall, and winter sun of <3 h. Bars = LSD; df = 19. Data week commencing.

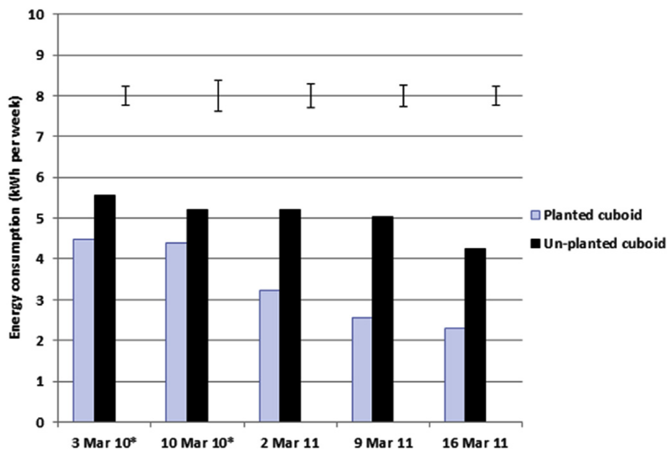

Fig. 8. Cold, wind and sun. Weekly energy consumption per cuboid, where weekly mean ambient temperature was cold, with wind, low rainfall, and winter sun of ≥3 h. Weeks with * represent periods where foliage cover was not complete. Bars = LSD; df = 11 for * weeks, and 19 for remainder. Data week commencing.

weather conditions, such as periods when temperatures were sub-zero.

3.8. Brick and ambient air temperatures compared at key times over 24 h

When brick temperatures were recorded continually it was observed that during cold periods (e.g. Feb. 2011) bricks in the PC treatment were significantly warmer than ambient air temperatures throughout (Table 3). During more milder periods in March, however, when solar gain is exerting a stronger influence the daylight temperatures were not significantly different, but the PC was still warmer at night (i.e. 21.00 and 3.00 h, Table 4). In contrast, UC bricks were rarely warmer than ambient when mean data sets are depicted (Tables 3 and 4).

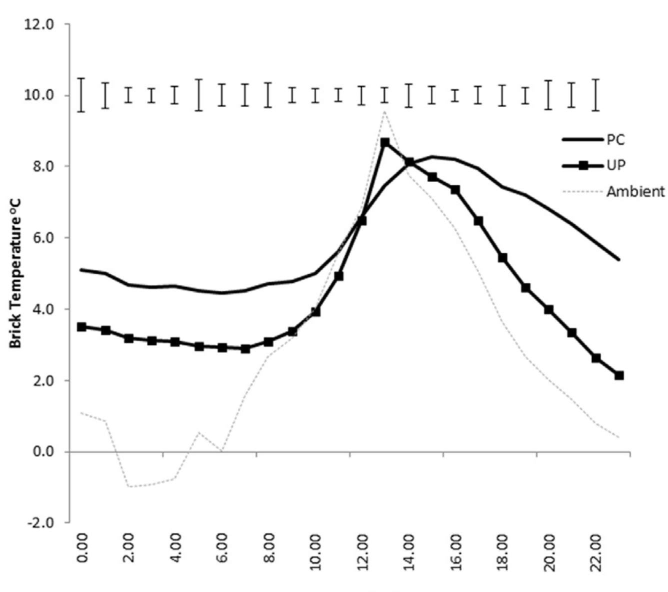

Fig. 9. Mean 24 h brick temperatures, March 4th 2011 when solar irradiation >120 Wm^{-2} between the hours of 8.00–15.00, and <120 Wm^{-2} thereafter; conditions dry with calm. Bars = LSD; df = 19.

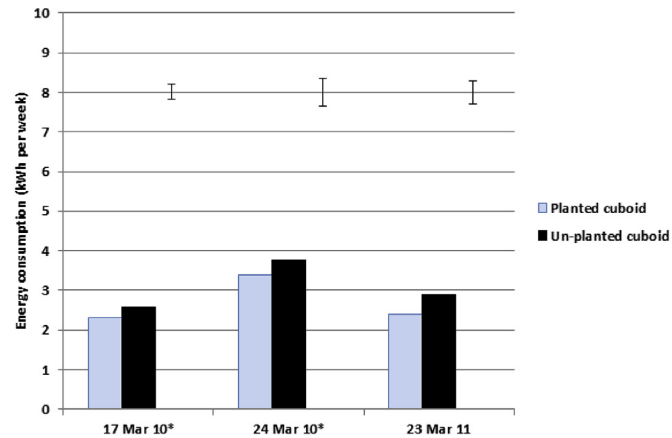

Fig. 10. Moderate and sun. Weekly energy consumption per cuboid, where weekly mean ambient temperature was moderate, calm, low rainfall, and winter sun of ≥3 h per day. Weeks with * represent periods where foliage cover was not complete. Bars = LSD; df = 11 for * weeks, and 19 for remainder. Data week commencing.

3.9. Energy consumption and associated carbon savings

When the mean weekly energy consumed per cuboid (Figs. 1, 3–6 and 8) is collated for each winter, the PC consumed a mean total of 38.3 kWh during the first winter (a recording period of 9 weeks), and 62.7 kWh for the second (a 17 week period); in contrast, the UC consumed 48.5 kWh in the first winter and 99.9 kWh in the second. Percentage energy savings attributable to the vegetated cuboids over these two recording periods were therefore 21% and 37% respectively. The higher saving in the second winter may relate to both the influence of the greater canopy density/coverage and the interactions of this with the prevalent weather conditions (the second winter being the colder of the two). Mean energy savings per week for each winter were calculated as 1st winter: 48.5–38.3 = 10.2 kWh savings/9 weeks = 1.13 kWh; 2nd winter: 99.9–62.7 = 37.2 kWh savings/17 weeks = 2.19 kWh. Converting these to CO_2^e (0.48357 × 4 i.e. cuboid volume 0.25 m^3) = 2.19 and 4.24 kgCO_2^e per m^3 per week for the first and second winter periods.

4. Discussion

4.1. Energy savings

The provision of vegetation around a brick cuboid reduced the energy used to maintain a stable temperature of 16 °C within the cuboids. The largest savings in energy due to the vegetation mantle were associated with more extreme weather scenarios, such as periods of cold or sub-zero temperatures, strong wind or rain. In specific weeks dominated by such weather scenarios, energy reduction could be as much as 40–50% less in the planted compared to the un-planted cuboids (e.g. weeks commencing 5 Jan., 19 Jan., 2 Feb., 9 Feb. and 16 Mar. 2011 (Figs. 3–6)). In addition, when comparing similar weather scenarios between the two winters, energy efficiencies were generally greater when the foliar canopies completely covered the cuboids compared to the earlier period when there was only partial cover, although the energy savings observed were not always statistically different. This would suggest the greater the volume of vegetation around the cuboid, the greater the thermal insulation service provided.

Consistent energy savings over a wide range of weather scenarios support the premise that vegetation can effectively insulate masonry, reducing the rate of heat transfer from an interior to an

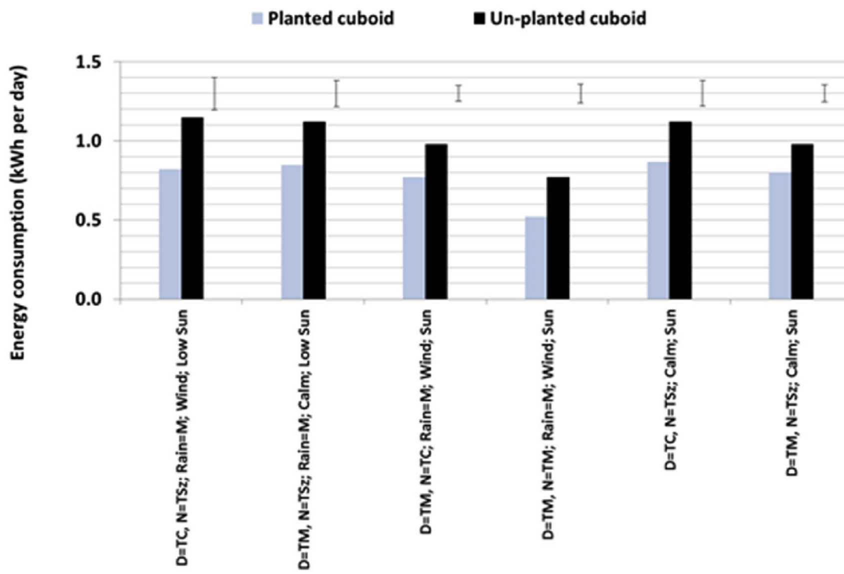

Fig. 11. Comparison of diurnal energy consumption per cuboid, selected 24 h periods Feb.–Mar. 2010; with associated weather (C = cold, D = day, N = night, M = moderate, Sz = sub-zero, T = temperature). All periods have incomplete foliage cover. Bars = LSD; df = 11.

Table 3
Mean brick temperatures compared to ambient, 21st Jan to 28th Feb 2011; df = 77. Significant differences in bold.

Difference between brick temp and ambient at 4 key times in 24 h.	Time	Mean temperature difference (°C)	ANOVA	LSD at 5%
Ambient v Un-planted	3.00	0.85	$P = 0.241$	1.44
	9.00	0.42	$P = 0.552$	1.41
	15.00	0.71	$P = 0.274$	1.28
	21.00	0.89	$P = 0.210$	1.39
Ambient v Planted	**3.00**	**2.64**	$\mathbf{P < 0.001}$	**1.32**
	9.00	**1.89**	$\mathbf{P = 0.004}$	**1.29**
	15.00	**1.45**	$\mathbf{P = 0.020}$	**1.21**
	21.00	**2.67**	$\mathbf{P < 0.001}$	**1.27**

exterior space. This validates the need for further work evaluating the use of green façades as a retrofit option for older housing stock.

4.2. Temperature profiles

In addition to net energy savings associated with planted cuboids, temperature differences between vegetated surfaces and bare brickwork were often evident. The surface temperature of foliage as determined by thermal images was invariably lower than the brickwork of a corresponding un-planted cuboid; suggesting greater energy release to the atmosphere from the bare cuboids. In contrast, direct measurements of brickwork temperatures indicated that the bricks of the vegetated cuboids tended to be warmer than bricks of the non-covered cuboids. Again this implies that the foliar canopy was insulating the brick wall, trapping thermal energy behind the leaves and thus retaining greater heat on the walls of the planted cuboids. Greatest temperature differences between bricks of the two treatments (and ambient air) occurred under the colder or wetter weather scenarios, and over the daily cycle during the late evening (21.00 h) and night (3.00 h) (Tables 3 and 4). This latter point has implications for energy demand scenarios in 'real' buildings. In the UK, peak winter domestic heating demand is in the evening [37], consequently reduction in the thermal gradient at these times has the potential for the greatest energy savings.

4.3. Insulation effects

The results presented here indicate that the presence of foliage around a heated brick structure is retaining heat largely through insulation. The mantle of foliage is effectively keeping heat trapped

Table 4
Mean brick temperatures compared to ambient, 1st to 25th March 2011. df = 49. Significant differences are in bold.

Difference between brick temperature and ambient at 4 key times in 24 h.	Time	Mean temperature difference (°C)	ANOVA	LSD at 5%
Ambient v Un-planted	3.00	1.16	$P = 0.194$	1.77
	9.00	−0.56	$P = 0.542$	1.85
	15.00	0.44	$P = 0.691$	2.21
	21.00	1.44	$P = 0.094$	1.64
Ambient v Planted	**3.00**	**3.56**	$\mathbf{P < 0.001}$	**1.63**
	9.00	0.35	$P = 0.669$	1.66
	15.00	0.34	$P = 0.745$	2.05
	21.00	**3.57**	$\mathbf{P < 0.001}$	**1.58**

behind it and slowing the dissipation of energy to the wider environment. As discussed above, the presence of foliage and increasing the cover and density of that foliage reduced the heat loss from the cuboids, particularly when there was a high thermal gradient, such as during sub-zero weather conditions.

Interestingly, there was also some anecdotal evidence that suggested leaves were not the only factor affording insulation around the cuboids. In non-vegetated cuboids there were differences in energy use between periods of deeper snow and periods when the snow cover was thinner (e.g. 300 mm deep on 6 Jan 2010 and only 13 mm on 15 Dec. 2010) with more energy used when the snow cover was thinner (Fig. 3). The snow itself being an insulating factor with deeper layers advantageous to energy savings. It cannot be excluded, however, that other less tangible variables between the weeks may also account for the differences.

4.4. Interactions with wind

The foliage around the cuboids may not simply have acted as a physical insulating material, but also interacted with wind and altered air flows around the structures. The foliage protecting the warm boundary layer of air that would form around the cuboids through increased aerodynamic resistance; thus reducing the 'wind chill' effect, i.e. the rapid removal of layers or pockets of localised warm air. Through a better retention of this warm boundary layer, the thermal gradient and convection rates of energy from the cuboid surface would be less, thus reducing overall energy consumption [10,11,25]. The potential for leaves to provide a 'shelter factor' in wind conditions, (drag caused by friction when air travels over a leaf surface) is well understood, an effect which is known to increase with foliage density [38]. Overall, the dense, full-canopy of 2011 shows significantly greater energy saving than the partially covered cuboids in 2010 in freezing rain and wind. This difference also being particularly evident in dry March winds (Fig. 8), where comparable energy use in the bare un-planted cuboids between the two winters, is in marked contrast to the reduced consumption as the cover over the planted cuboids becomes more extensive/dense. A denser canopy may be more effective at reducing air flow and trapping pockets of warm air against the brickwork. Similar principles have been cited for hedges around domestic houses, where closed, densely-formed hedges were deemed twice as efficient as open rows; and where the infiltration of cold air increased significantly when gaps were present in the canopy [39].

The data for the cuboids is consistent too with the use of shelterbelt trees to reduce heating demand within buildings [10,11,25]. It is notable that both energy consumption and brick temperatures were relatively consistent in the planted cuboids compared to frequent flux (oscillations) recorded in the un-protected, suggesting that vegetation was moderating the weather effects on the masonry. This is important when considering the cost/benefit of vegetated walls, since walls facing the prevailing cold or strong winds are likely to gain the highest energy savings. In addition, there was evidence that promoting denser, thicker foliage extends the advantages by further reducing energy demands (e.g. Fig. 3).

This ability to buffer against weather extremes also indicates that optimal benefits of green façades may be experienced for those houses located in exposed areas. This is because air exchange in the building envelope is driven by pressure difference caused by the temperature differential between inside and outside (stack effect); and enhanced by windblown air currents [40]. In summary, this means the greater the temperature differential (thermal gradient) *and* the greater the wind velocity, the greater the heat loss. This exponential effect was first illustrated in wind tunnel experiments by Harrje et al. [39] and subsequently highlighted by Hutchinson and Taylor [23] in their promotion of shrub plantings to protect the exposed walls of buildings from wind. Despite this research being 30 years old, few house owners, or even professional landscape architects seem to fully appreciate the functional role plants play in this respect – rationale based on aesthetics often being a stronger driver in design criteria [41–43].

4.5. Influence of precipitation

Another factor that may be pertinent to the use of foliage against a wall is the extent to which it keeps the wall dry during rainfall periods. There was a marginal increase in energy efficiency associated with planted cuboids over non-planted when rain was an additional factor (when a full canopy was present there was an overall 42% saving in energy in cold, wind and rain scenarios (Fig. 4) compared to a 39% saving in cold and wind alone (Fig. 5)). Again ancillary factors could also explain these differences, but it was certainly evident from visual observations that leaves intercepted and deflected precipitation away from the wall; a result reported elsewhere [26,44]. The extent to which 'dry' walls affect heat loss compared to 'wet' walls needs further research, but as water is a better thermal conductor than air it might be assumed it is advantageous to keep the walls dry. The observations though, challenge the commonly-held notion that *Hedera* around a wall invariably makes it damper. The observations here agree with previous research that indicated *Hedera* façades reduced fluctuations in relative humidity compared to exposed walls [45]. This being compatible with the concept that vegetated walls are kept drier after precipitation, but may retain moisture and higher humidity at other times. Whether these aspects contribute to the bioprotection or biodeterioration of walls is still unclear [45].

4.6. Vegetation and solar gain

One disadvantage of evergreen façades is that due to their shading effect they may reduce the ability of winter sunlight to contribute positively to the thermal balance of the building (solar gain). Recent simulations for green walls in Portugal suggest they save energy when placed on north, west and east walls, but not south facing walls [46]. In the study presented here, however, solar gain did not make a significant difference to results observed until mid-March, suggesting that loss of mid-winter solar gain to masonry is not a significant factor for energy efficiency, at least perhaps for countries in the mid to high latitudes. This supports previous models [10] that suggest the benefits of wind protection from trees/shrubs outweighs the disadvantages associated with reduced solar gain in winter. Notably, Liu and Harris [11] working in Edinburgh, UK, found greater energy consumption during winter in the presence of direct sunlight compared to overcast days, as periods of clear sunlight also tended to correspond to anticyclone conditions with low winter air temperatures. More recently Bolton et al. [47], suggested that loss of winter solar gain on green façades is significant to the building's energy balance, but only when ambient air temperatures >12 °C. The relative importance of winter solar gain may depend on latitude and the primary climatic conditions of different locations. It is notable in this study too that as solar intensity increased from mid-March, solar radiation and heating to the masonry quickly dissipated after sunset on the non-vegetated cuboids, but heat was retained until the late evening behind foliage on vegetated cuboids; although this did not always result in significantly reduced energy consumption at this scale.

4.7. Implications for vegetation use on real buildings

The primary objective of this research was to determine how green façades interacted with different winter weather scenarios in terms of energy conservation; when a consistent physical thermal model system (cuboid) was employed and replicated. The research did not aim to investigate the full range of additional factors normally associated with the thermal dynamics and energy consumption of real buildings. Nevertheless, some inferences can be made from the data, albeit cautiously. The data derived from this study was used to generate figures for potential savings in greenhouse gas emissions (carbon equivalent units). Based on these small-scale brick units in the absence of artificial insulation, savings of 2.19 and 4.24 $kgCO_2^e$ per m^3 per week for the first and second winter periods respectively, were recorded. If these weekly values are then scaled up to represent heating demand for a UK house for 21 weeks (1 Oct.–1 Mar.) they relate to reduced emissions of 45.9 and 89.0 $kgCO_2^e$ per m^3 per winter. The cuboids, however, were not houses and differ from even Victorian brick terraced housing, in that the bricks were not mortared (thus potentially increasing draught) and the cuboids had a very high surface to volume ratio. An east London terraced house with floor area of 80 m^2 and ceiling height of 2.5 m (air volume 200 m^3) has a mean 'volume to exterior wall area' ratio of 3.5:1 [48]. In contrast the 'volume to exterior wall area' ratio for the cuboids was 0.12:1 (volume 0.25 m^3/total surface area 2.04 m^2 including roof); this higher exterior wall area ratio would significantly influence rate of heat loss in the cuboids. On the assumption that heat loss is proportional to the volume/surface area ratio then the terraced house would be 29.2× more efficient at retaining energy (i.e. 3.5/0.12). If it was a mid-terrace property, only two walls (not four) would be exposed to exterior weather conditions, i.e. doubling the efficiency of heat retention (58.4× more efficient than a cuboid). Therefore, typical CO_2^e savings for a mid-terraced house of 200 m^3 are likely to be in the region of 157–239 $kgCO_2^e$. This compares to values of 395 $kgCO_2^e$ quoted for adding solid wall insulation (or where there is a cavity recess, cavity wall insulation) to a mid-terrace property [49]; and as such, vegetation would seem to have a strong role to play in adding extra insulation to such properties. This is especially so, as the canopy densities evaluated in the research were low compared to what might be achieved in mature façades. These data sets presented here, however, make a number of assumptions that need to be tested and verified *in vivo* with full scale studies. It should also be noted that the parameters associated with the brick cuboids would be very different from a typical house. Many non-insulated terraced brick houses lose heat through windows, door and roofs; factors not tested here, and certainly not areas where climbing plants would be welcome. The cuboids walls were not sealed, rendered or thermally insulated from the inside with plasterboard or similar materials. The cuboids had very little air mass within them, thus restricting the amount of air movement between the internal and external environment. Thus any analogies to real buildings need to be seen in this context.

Further research is required therefore, to scale up the factors investigated to real buildings, but also to explore how species choice might affect the thermal dynamics of a building wall. Nevertheless, the data presented here suggests vegetated façades using climbers/wall shrubs should be given greater precedent when considering strategies to insulate buildings in winter. This is especially so of older, domestic properties, such as brick terraced housing where alternative retro-fit opportunities may be less easily implemented – due to restrictions of space, Local Authority planning (e.g. conservation areas), access, or type of construction (e.g. the lack of cavity wall aperture). Future research needs to compare vegetation approaches to other forms of building insulation and design options, to determine both relative (and combined?) benefits. Nevertheless, these results are encouraging in that home-owners already utilise climbing plants and wall shrubs for aesthetic purposes around their properties; yet with some adjustments to landscape design and plant positioning, additional benefits in terms of home energy savings could be manifest readily quickly. The advantage of using plants too, is that a range of additional eco-system services may be provided in addition to thermal insulation, many of which are not supplied by the artificial alternatives.

5. Conclusions

The use of replicated structures in field conditions representing typical UK winter weather scenarios, demonstrated that the presence of foliage consistently reduced diurnal energy consumption and associated carbon emissions. Throughout winter, foliage-covered brick cuboids maintained temperatures higher than ambient; particularly in the evening with associated potential to reduce peak-energy demand. The trapping of warmed air is a principal function of commercial insulation products, (as still air has low thermal conductivity), suggesting that vegetated walls can offer similar characteristics. Furthermore, vegetation reduced convective heat loss particularly through reduction in wind chill and protection from precipitation. Reduction in convective heat loss is another key factor in retrospective fitting of insulation for existing housing, e.g. through draught proofing. Loss of solar gain had no effect on the efficacy of vegetated walls (until early-spring); to the contrary, vegetated walls remained warmer than controls in nocturnal hours following days with notable solar irradiance in winter.

This study suggests that various thermo-regulatory mechanisms coalesce to provide vegetation with demonstrable efficacy. Vegetation could be effective, either where cavity insulation is not practical or as a sustainable method of enhancing existing insulation. Annual efficacy was found to be strongly weather dependant, with precipitation and temperature extremes increasing the magnitude of the effects. This is critical, not just because of the wide potential application for buildings in exposed areas or northern parts of the UK and elsewhere, but also since frequency, duration, and magnitude of winter precipitation events are likely to increase in certain temperate regions under climate change.

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