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The Effect of Climate on Thermal Loads in Living Walls

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Abstract: This study analysed the impact of living walls on energy-efficient residential buildings in major Australian cities with varying climates. The aim was to identify and quantify the shading and evapotranspiration benefits of living walls using calibrated thermal simulation software. Empirical correlations were applied to replicate the evapotranspiration effect in the simulation. Building dynamic thermal modelling was undertaken with the widely-used AccuRate Sustainability energy rating software. Two house designs were used in the simulation, applying various scenarios to assess the benefits of living walls in various Australian cities. The results showed that living walls provided the most cooling in warm and dry climates such as Perth and Adelaide, with minimal benefits in tropical regions such as Darwin. In temperate climates, living walls had little impact on heating, but in colder climates, they increased heating demand. Homes with insulated walls are common in modern residential construction. For such homes, the evapotranspiration effect rather than the shading or insulation characteristics of the living wall became the primary mechanism for reducing cooling loads, particularly in drier climates. When applying a single living wall for idealized models a potential cooling savings in cooling energy of 10–16% was determined, whereas for typical home designs this saving reduced to below 1%. It was found that the benefits of living walls are comparable to or lower than simpler, more cost-effective passive strategies such as adjusting building orientation or using light-coloured walls.

Keywords: urban heat island; living wall; thermal load; nature-based solutions; green wall; green infrastructure; vertical garden; sustainable drainage systems

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1. Introduction

The urban heat island (UHI) effect leads to higher temperatures in urbanised areas compared to surrounding sub-urban or rural areas. This effect is largely associated with a high concentration of urban infrastructure with low light or radiation reflectivity resulting in the urban area absorbing increased solar radiation [1]. The UHI effect increases the local temperature within the microclimate. The impact on heating ventilation and air conditioning (HVAC) systems is that UHI reduces HVAC efficiency which further increases peak demand. As a result, the heat rejected to the environment increases which causes a feedback loop, adding more heat into the microclimate, further exacerbating the heat island effect. The use of materials with low albedo coefficients, a reduction in vegetated areas and the generation of anthropogenically-sourced heat have caused the UHI effect to increase significantly in highly populated regions [2]. A promising solution to this effect is to increase the proportion of urban vegetation [3]. Additionally, urban morphology can influence heat retention by increasing shortwave radiation and trapping longwave radiation, leading to greater heat storage in cities [4]. Several mitigation techniques have been suggested, including air ventilation, shading of buildings, planting of vegetation in green roofs or living walls, application of irrigation water and external use of high albedo materials on building surfaces [5]. Of these, planting of vegetation is the most widely applied mitigation measure that can achieve significant energy savings through temperature reduction [6].

Living wall (LWs) are contemporary vertical greenery systems that help expand urban green spaces. They offer the flexibility to be installed almost anywhere and provide the recognized benefits of urban greenery, such as cooling, enhancing air quality, supporting biodiversity, providing enhanced aesthetics, improving psychological well-being and reducing energy consumption through increased building insulation [7]. Figure 1 shows a (LW) in Antwerp, Belgium. A recent study found that the most important factors affecting the successful establishment of a LW are plant species selection, substrate type and irrigation regime. The study also found that the interactions between plants, substrates and irrigation are important. Significantly, plant selection was found to be more important than either substrate or irrigation selection [8].

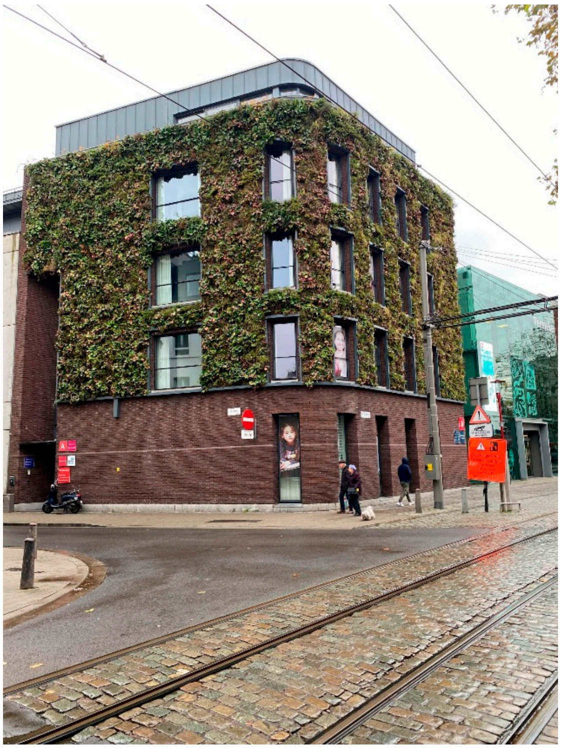

Figure 1. A living wall in Antwerp, Belgium.

The thermal performance of LWs is influenced by shading, evapotranspiration (ET) and increased thermal mass [9]. The installation of a LW on a building's external walls provides shading by intercepting incoming solar radiation [10]. Shading can be correlated to an additional structure with thicker greenery consistent with a vertical greenery system [11]. Furthermore, LWs reduce the microclimate temperature via ET. This is achieved by the plants transferring absorbed solar radiation and sensible heat into latent heat through transpiration and evaporation of water [12]. The effect of ET is a unique aspect of vegetation that can be provided by a LW, which other passive energy efficiency measures, such as adjusting building orientation or using light-coloured walls, are not designed to deliver. For instance, temperature differences recorded between a bare control wall and a LW were up to 15 °C in summer in a study conducted in Adelaide, Australia [13]. In a similar experimental study conducted in Northern and Central Italy, temperature differences between 12 °C and 20 °C were recorded between a LW and its bare control wall [14]. Finally, due to its thermal mass and resistance, heat transfer through the wall is greatly reduced [15]. All components of a LW system contribute to thermal mass, including its substrate, structural materials and plants [16]. The thermal resistance and mass of the LW will delay and reduce heat transfer to the building [17].

This study examined the impact of LWs on modern, energy-efficient residential buildings across Australia's major cities, each with different climates. This study also provides practical insights into the energy efficiency benefits of living walls compared to simpler passive design strategies, such as light-coloured walls or building orientation, which is a new and unique contribution to the field. The goal was to identify and quantify the specific benefits of shading, ET and thermal mass using simulation software that was calibrated using the results of an experimental living wall investigation that was conducted at the University of South Australia (UniSA) in Adelaide [8]. The experimental wall is shown in Figure 2.

Figure 2. Experimental Living Wall at UniSA, monitored from December 2016 to March 2020 (after [12]).

2. Materials and Methods

2.1. Simulation Tool

Simulation and modelling were conducted using an Australian benchmark energy rating software package, AccuRate Sustainability [18]. This is a tool used to calculate the annual energy needed to maintain building comfort. It is one of three programs accredited by the Nationwide House Energy Rating Scheme (NatHERS) for estimating energy efficiency in Australian homes for compliance with the national building code. AccuRate Sustainability was developed by Australia's national science agency, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in partnership with the Australian Government Department of Climate Change. The AccuRate program has also been assessed against the International Energy Agency BESTEST, which found that it compared well against their eight reference programs from the US and Europe.

The AccuRate software tool is mathematically rigorous (For a full and up-to-date description of the AccuRate Sustainability mathematical model, see the Nationwide House Energy Rating Scheme (NatHERS) website: https://www.nathers.gov.au/Whole-of-Home-Calculations-Method, accessed on 25 February 2025), highly regarded and is widely used for modelling building energy in Australia [19]. In this study, AccuRate was used to run simulations across various climate zones using 1-D modelling for ventilation and heat flow, effectively estimating the impact of LWs on heating and cooling loads. The software requires information on the material dimensions and properties. For example, key concepts include emissivity and thermal resistance. Emissivity is a measure of how a surface emits or reflects heat energy and is calculated by the amount of energy emitted or radiated from a material's surface. Thermal resistance per unit area (R-value) is a measure of the resistance to heat flow through a specific thickness of a material.

The AccuRate software enables users to customize building designs by selecting various materials for walls, roofs, windows and floors, and by adjusting thicknesses and insulation [20]. It calculates heat flow based on dimensions, air gaps and R-values but excludes thermal bridging. Zones within the house are categorized as conditioned (such as living areas) or unconditioned (such as garages), with pre-set occupancy, thermostat settings and shading. It also simulates window and door operations, for example by assuming windows are open when the outside temperatures are cooler. House models assume no nearby shading and adjust building orientation for passive design.

The living wall was thermodynamically approximated within a transient building thermal model. This approximation involved replicating the thermal resistance and capacitance of the living wall as well as changing the outdoor temperature by applying the wet bulb effectiveness to replicate the evapotranspiration effect. This was the only boundary condition adjusted, after which all other boundary conditions were defined by the building thermal model. To accurately model the impact of a LW, appropriate thermo-physical representations of the LW were taken from a previously published experimental study undertaken by the same research team [12]. Two house designs were used in the simulation and analysis, with various scenarios applied to identify and quantify the benefits of the LW in seven Australian cities that experience different climates.

2.2. House Layouts and Locations

To investigate their thermal properties, two house designs were selected. House A consisted of a simple box design, with a focus on specific elements such as building orientation relative to the LW. House B represented a typical single-storey house found in Australia. Both houses were insulated to reflect standard residential designs.

2.2.1. Layout and Building Elements of Houses A and B

House A represented a simple, idealised box-shaped single-story home with a 100 m^2 floor area (10 m × 10 m) and a 2.4 m ceiling height, as shown in Figure 3. Modelling this design enables the specific impact of the LW to be identified. It consisted of a single room (4 m × 5 m) that covered 20% of the total floor space. Designed to maximize the impact of LWs, it featured dark external walls, a light-coloured roof, one door and two sliding windows; these features reduce roof heat gain in summer while increasing heat flow through the walls. The house had standard Australian brick veneer walls with insulation and both the living and bedroom areas were considered as conditioned zones, meaning that no part of the house was unconditioned.

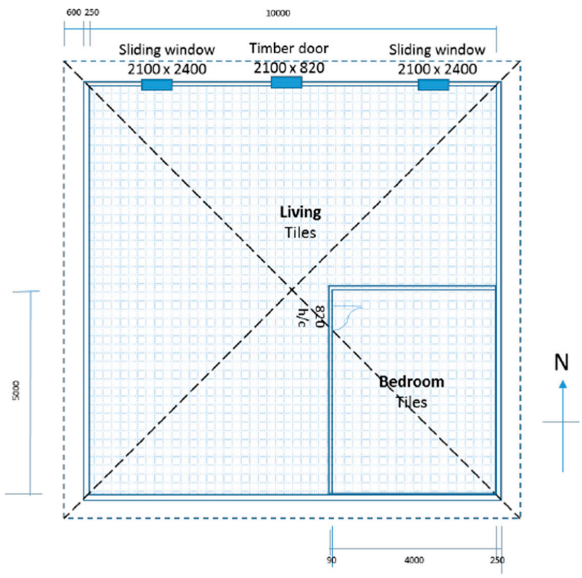

Figure 3. Floor plan of House A with a north-facing orientation.

House B represented a larger, typical single-story detached home with four bedrooms and a total floor area of 205 m^2, as shown in Figure 4. It also included a garage, which was an unconditioned area. Unlike House A, House B is an example of an actual house design and modelling will show the impact of the LW in this case only. The design is more complex, with more rooms and windows, which potentially could reduce the effectiveness of LWs due to less available wall space. Its north-facing orientation and 6-star energy rating from AccuRate Sustainability reflect typical Australian residential construction. The medium-coloured roof and external walls of House B are likely to lead to more heat gain through the roof and less shading impact compared to House A's darker walls. Detailed descriptions of Houses A and B are provided in Table 1.

Table 1. Description of House A and B elements.

Elements	Descriptions	
	House A	House B
External wall	Brickwork 110 mm + air gap 90 mm + R2.5 glass fibre + plasterboard 10 mm (dark colour wall)	Brickwork 110 mm + air gap 31–65 mm + R2.5 glass fibre + plasterboard 10 mm (medium colour wall) Rendered brick veneer with plaster (Cement:sand 1:4) + brickwork 110 mm + air gap 31–65 mm + R2.5 glass fibre + plasterboard 10 mm (medium colour wall) Cavity brick with brickwork 110 mm + air gap 90 mm + brickwork 110 mm

Table 1. *Cont.*

Elements	Descriptions	
	House A	**House B**
Window/ Sliding door	Aluminium framed single glazed clear; glass thickness 4 mm Door (solid) hardwood	Aluminium framed single glazed clear; glass thickness 4 mm
Door (external)	-	Solid hardwood thickness 50 mm Steel garage door thickness 2 mm
Door (Internal)	Timber (solid) Mountain ash; 50 mm thickness	Timber (solid) Mountain ash; 50 mm thickness
Floor	Concrete slab + Tiles	Concrete slab + tiles Concrete slab + carpet Concrete slab bare
Ceiling	Plasterboard 13 mm + R4.0 glass fibre insulation	Plasterboard 13 mm + R4.0 glass fibre insulation Plasterboard 13 mm
Internal wall	Plasterboard on studs (plasterboard 10 mm + air gap 90 mm + plasterboard 10 mm)	Plasterboard on studs + R2.0 (plasterboard 10 mm + R2.0 glass fibre + plasterboard 10 mm)
Roof	Hip roof—Metal deck (steel); light colour 30% solar absorptance with 0.90 E + reflective	Gable roof—Metal deck (steel); medium colour 50% solar absorptance with 0.90 E + reflective

R: thermal resistance, E: emissivity.

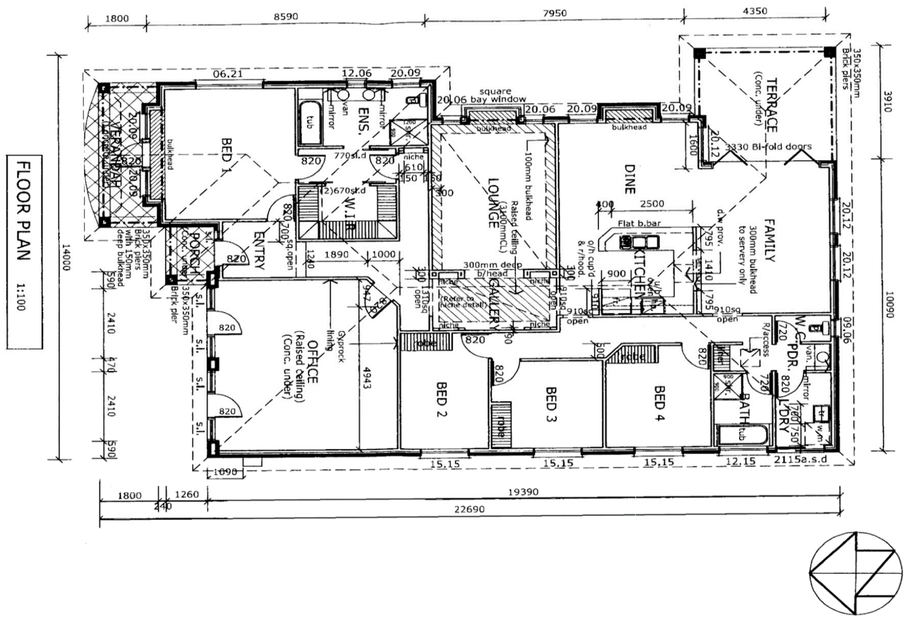

Figure 4. Floor plan of House B with a north-facing orientation.

2.2.2. Location for Simulation and Analysis

Table 2 lists the NatHERS climate regions, Koppen–Geiger classifications, as well as the mean annual humidity, rainfall and temperature for these cities. The cities fall into four Koppen–Geiger climate classifications. Darwin is tropical, while the others are temperate but vary in characteristics. Sydney and Brisbane are subtropical and humid. Perth and Adelaide are Mediterranean, with Perth being wetter and slightly warmer, and Adelaide being the driest location with the lowest humidity. Melbourne and Hobart are oceanic, with Melbourne being warmer and more humid but receiving less rainfall than Hobart. Darwin has typical tropical wet and dry seasons, while the other cities experience four distinct seasons. Hobart is the coldest location, needing minimal cooling. The case study for House B was only applied to Adelaide.

Table 2. Climate characterization of selected locations.

Cities	Koppen-Geiger Classification	Mean Annual RH (%) *		Mean Rainfall (mm) *	Mean Annual Temp (°C)	
		9 a.m.	3 p.m.		Max	Min
Darwin	Aw	71	54	1725.1	32.0	23.2
Sydney	Cfa	69	57	1081.1	22.4	13.5
Melbourne	Cfb	71	55	585.6	19.8	9.4
Brisbane	Cfa	63	52	1011.5	26.6	16.4
Adelaide	Csa	62	47	547.6	22.4	12.3
Perth	Csa	63	47	733.2	24.7	12.8
Hobart	Cfb	68	58	613.5	17.0	8.4

Aw: Tropical savanna, Cfa: temperate humid subtropical, Cfb: temperate oceanic, Csa: temperate Mediterranean climate, RH: relative humidity, * data from [21].

2.3. Modelling Living Wall Properties

To replicate the LW, shading, thermal mass and resistance characteristics needed to be simulated within the AccuRate Sustainability model. Furthermore, a methodology was developed to approximate the impact of the ET cooling effect.

2.3.1. Shading and Thermal Mass

To model the thermal characteristics of LW materials in AccuRate Sustainability, a notional wall element made from soil was defined which had the same thermophysical properties as the LW. These characteristics include thermal resistance, thermal capacitance and radiation properties. The external radiation properties were set with no solar radiation transmission, a solar absorptivity of 0.9 (representing a dark surface) and a thermal emittance of 0.9, which is typical for LWs. The LW was added as a homogenous external wall element with matching configuration, thermal resistance and capacitance. AccuRate Sustainability provides resistance and capacitance values for built-in materials. Specific heat capacity and thermal mass calculations for LW materials are listed in Table 3, with the thermal capacitance equation shown in Equation (1).

$$m_t = m \times C_p \quad (1)$$

where m is the mass (kg) and C_p is the specific heat capacity (kJ/(kg·K)).

The weights of the LW pots, panels, substrate and plants were measured from the experimental LW shown in Figure 2. The soil substrate was assumed to be potting mix. The specific heat capacity for the LW pots and panels, which were made of polypropylene, was 1.920 kJ/(kg·K). The wet substrate had a specific heat capacity of 1.480 kJ/(kg·K). For the plants, an average specific heat capacity of 1.761 kJ/(kg·K) was used [22].

From Table 3, the calculated thermal mass per m^2 is 51.8 kJ/°C (=51.8 kJ/K). Soil properties for the LW are presented in Table 4.

Table 3. Calculation of thermal mass of individual living wall materials.

Item	Quantity	Unit Weight (kg)	Total Weight (kg)	Specific Heat Capacity, C_p (kJ/(kg·K))	Thermal Mass (kJ/K)
Living wall pots	144	0.3	41.2	1.920	79.1
Living wall panels	18	1.9	33.4	1.920	64.1
Substrate with 40% moisture content	144	1.0	142.1	1.480	210.3
* Plants	144	-	11.2	1.761	19.7
Total thermal mass for a 7.2 m^2 living wall					373.2
Thermal mass per m^2					51.8

* total dry weight of plants from the experimental living wall was taken.

Table 4. Soil properties taken from the AccuRate Sustainability Guide (Energy Inspection 2018).

Name	Thickness Required	Resistance (Heat Flow Up) (m^2·K/W)	Resistance (Heat Flow Down) (m^2·K/W)	Capacitance (kJ/(m^3·K))
Soil (average)	Yes	0.830	0.830	1613.0

The soil capacitance was 1613.0 kJ/(m^3·K) and the thermal mass of the LW was calculated as 51.8 kJ/(m^2·K). Therefore, the thickness of the soil carrying the equivalent thermal capacitance is calculated as 31 mm. Compared to that of a house brick, the thermal mass of the LW was low, and therefore any approximations associated with this calculation will have a negligible impact on the heat flow calculation through the LW.

Table 5 shows the LW elements (layers 1 and 2). The air gap was 20 mm, matching the experimental gap between the LW and the building façade (see Figure 2). Other building model elements (layers 3 to 6) were chosen from the AccuRate Sustainability built-in properties. Air gaps include the emissivities of the two adjacent surfaces and the effective emissivity, E.

Table 5. Living wall elements in AccuRate Sustainability.

	Layer	Material	Thickness (mm)
External	1	Soil (average) (emissivity and solar absorptance = 0.9)	31
|	2	Air gap vertical 17–30 mm (20 mm nominal) ventilated non-reflective (emissivity of surfaces = 0.9)	20
|	3	Brickwork; generic extruded clay brick (typical density)	110
|	4	Air gap vertical > 66 mm (90 mm nominal) unventilated non-reflective (emissivity of surfaces = 0.9)	90
|	5	Glass fibre batt: R2.5 (where R = thermal resistance)	110
Internal	6	Plasterboard	10

2.3.2. Evapotranspiration Representation

For each simulated condition, the external wall was replaced with a LW representation. The house postcode determined the climate zone and the appropriate weather data file, which included hourly temperature, specific humidity and atmospheric pressure. Studies have shown that LWs act as evaporative cooling sources through plant ET, reducing local temperatures by increasing humidity [23]. The results from the full-scale experimental LW found a correlation between this humidification process and wet-bulb effectiveness (η_{wb}), with an average η_{wb} of 0.36 [12]. This wet-bulb effectiveness is used to determine the air temperature that the external LW is exposed to, reflecting the direct impact of ET from the LW. Using the local data from the NatHERS RMY file, a modified temperature adjacent to the LW was calculated from Equation (2) [24]:

$$\eta_{wb} = \frac{T_{db} - T_{air\ new}}{T_{db} - T_{wb}} = 0.36 \tag{2}$$

where η_{wb}: wet-bulb effectiveness, T_{db}: dry-bulb temperature measured at 1000 mm away from the LW, T_{wb}: wet-bulb temperature measured at 1000 mm away from the LW, $T_{air\ new}$: updated air temperature adjacent to the LW.

NatHERS Reference Meteorological Year (RMY) climate files were compiled from the Australian Bureau of Meteorology (BOM) raw climate data and were used to simulate a typical year for every climate zone in Australia. The RMY climate files were based on 26 years of historical weather data from the period 1990–2015 [25]. The wet-bulb temperature was calculated from the atmospheric pressure, dew point and temperature using the method of [26]. For simulating the ET effect of the LW, the weather file was modified by applying the new dry bulb temperature ($T_{air\ new}$) to reflect the impact of LW. This adjustment was made for temperatures above 25 °C from September to May, except in Darwin where cooling is needed year-round. These changes were saved in the AccuRate Sustainability library weather file, creating a modified weather file (Mod.WF) used in the LW model simulations. The original weather file (Ori.WF) was also used to compare results with and without the effects of ET. Figure 5 shows the temperature on Adelaide's hottest day, 13 February, with and without the effect of ET. Ori.WF represents the original ambient temperature, while Mod.WF shows the modified temperature with the effects of ET.

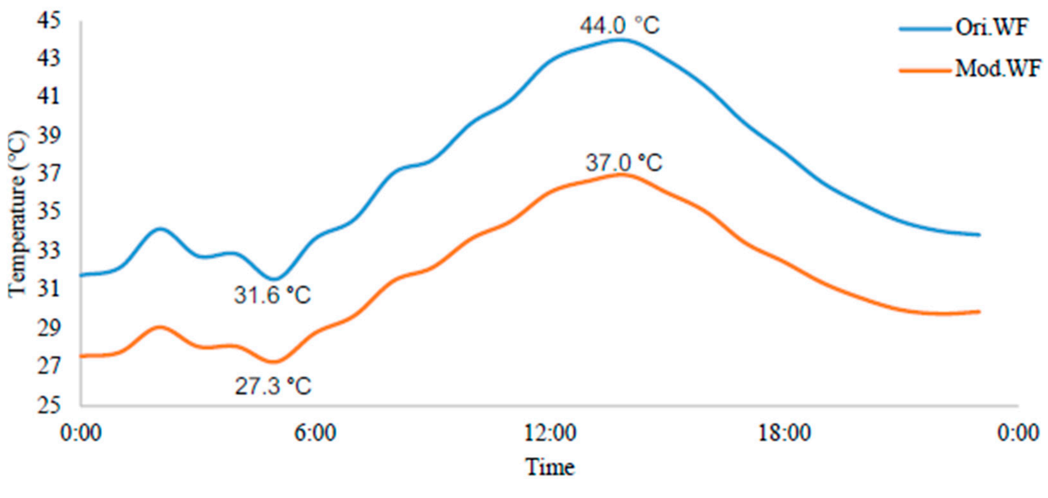

Figure 5. Hourly air temperature for the hottest day of the Reference Meteorological Year (RMY) for Adelaide, which was on the 13 February without (Ori.WF) and with (Mod.WF) evapotranspiration effects.

The modified temperature (Mod.WF) for the hottest day of the RMY for Adelaide at its peak was 7 °C lower than the original dry bulb temperature (Ori.WF) without ET effects, with a consistent reduction in air temperature between 4–7 °C throughout the day. This reduction can be expected to reduce the transmission of heat flow into the building and will operate in combination with the shading effect of the LW.

2.4. Living Wall Thermal Load Simulation

To model the impact of the thermal mass and shading aspects of the LW without the impact of ET, LW external building wall elements were applied before running the simulation. This step involved applying the original weather file (Ori.WF) with an unmodified ambient temperature. This result represents the impact of a hypothetical LW that has no ET effect.

To determine the impact of the ET effect, a novel process of subtraction was implemented. With a modified ambient temperature (Mod.WF), the impact on the simulation is that it will apply this temperature to the whole building, which is expected to significantly overestimate the impact of the ET effect. Therefore, to model the isolated impact of ET on a specific wall, a separate process was applied. First, the same model was simulated, applying the modified weather file containing the cooler ambient conditions (A). This condition applies the ET effect to all surfaces, including all walls and the roof. Second, the LW was replaced with an adiabatic boundary where no heat flow occurs, as defined by a wall with insulation at R10. This model was then re-run using the modified weather file (B). Finally, this model with the adiabatic boundary was re-run with the original weather file (C).

The first simulation assumes that all exposed exteriors of the house (external walls and roof) are subjected to the modified temperature. Therefore, C-B approximates the additional heat flow from all non-LW surfaces, including the roof, that need to be added to the first simulation, to offset the additional cooling applied to the non-LW surfaces. Therefore the thermal load into the building is defined as A + (C − B).

This methodology was tested against simplified box models of a building without doors and windows to verify the technique. This involved modelling one surface with all other surfaces being set as adiabatic. The addition of the results from each of these simulations was found to correspond to the case of the original box model simulated with non-adiabatic surfaces. This method effectively applies the microclimate to only the LW, adding other heat flows through the building. This approximation includes the heat flow through the ground, the impact of solar radiation on the walls and roofs and ventilation through doors and windows, which are all temperature-dependent. The main advantage of this technique is that it allows rigorously, yet computationally efficient, LW simulations to be conducted using a simple modification of the weather file together with a widely used building simulation software package. Each of the three required simulations took approximately one minute, making the adopted approach acceptably time-efficient.

Simulation Scenarios

To investigate the impact of LWs, nine thermal load simulation scenarios were developed, as shown in Table 6. House A, with its idealized design and small size, exaggerated the LW effects, which allowed for more detailed exploration of the mechanisms through which the LW delivers thermal benefits to the building. House B, with a more typical design and complex heat transfer pathways, was likely to show a reduced impact from a single LW. The LW was compared to other low-cost passive design features such as building orientation and light wall colouring. Light-coloured roofing is comparable to shading since it reduces solar radiation absorption. In Table 6, Condition I is the control scenario where the house was simulated without any LWs, while Condition II includes LWs on all four walls with the original weather file used to establish the shading-only impact. To provide a comparison with non-LW passive design options, the house orientation was varied in Condition I, while Condition V was used to investigate the impact of light coloured external walls. These two non-LW conditions were compared to LW applications (Conditions II, III and IV). All five conditions were tested for House A. In addition, a sub-set of these conditions was also investigated across Australia by varying house orientation and applying a LW to one wall (Condition III) or all walls (Condition IV).

Table 6. Condition number and scenarios for house thermal load simulation.

Condition	Scenario	No of Living Walls
I	No living wall *	0
II	Dry living wall	4
III	Living wall on one facade	1
IV	Living wall on all facades	4
V	Light colour external walls	0

* Control scenario.

AccuRate Sustainability was used to determine the annual cooling load for each configuration. For House B, the LW was applied only for Adelaide and for the cases of one LW (Condition III) and all walls (Condition IV) for the given orientation of the house. The purpose of simulating these two cases was to examine a realistic range of LW benefits for a typical Australian house. Figure 6 illustrates Condition III for House A, with one LW on one facade.

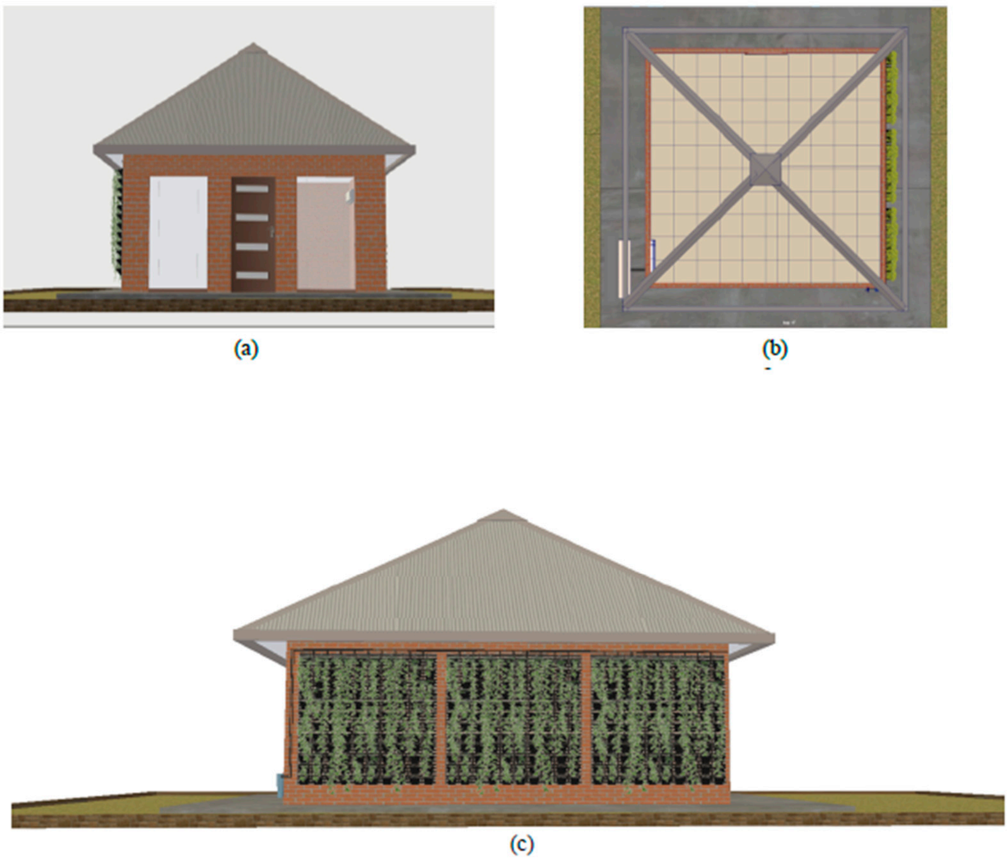

Figure 6. Illustration of one living wall on House A representing Condition III (**a**) front view, (**b**) top view and (**c**) side view.

2.5. Electrical Cooling Load Calculation

The main value of a LW, like other passive design features, is to reduce air conditioning needs. This analysis assumes some air conditioning is still required. The impact on the electrical energy consumption of a nominal air conditioner applied to houses A and B was determined in order to define the primary energy efficiency benefit of a LW. The study did not include the heating load from air conditioners during winter. The efficiency of an air conditioner is measured by the coefficient of performance (COP), which is the ratio of thermal cooling produced to electrical energy used. COP for cooling decreases with higher outdoor temperatures, so electrical energy consumption varies non-linearly with the building's thermal energy load [27]. Figure 7 shows this variation in COP with outdoor temperature for various locations in Australia, based on indoor temperature settings as defined by AccuRate Sustainability. The COP values were calculated based on the temperature-dependent performance of the air-conditioning system used in the simulations. For example, in Darwin, where outdoor temperatures are consistently high, the air conditioning system operates more frequently at lower efficiency points on the COP curve, resulting in a lower average COP. In contrast, in milder climates like Melbourne, the air conditioning system operates at higher efficiency points, leading to a higher average COP. Since LWs reduce energy consumption more on hotter days due to the effects of ET, it is important to investigate their impact on air conditioning electrical energy consumption.

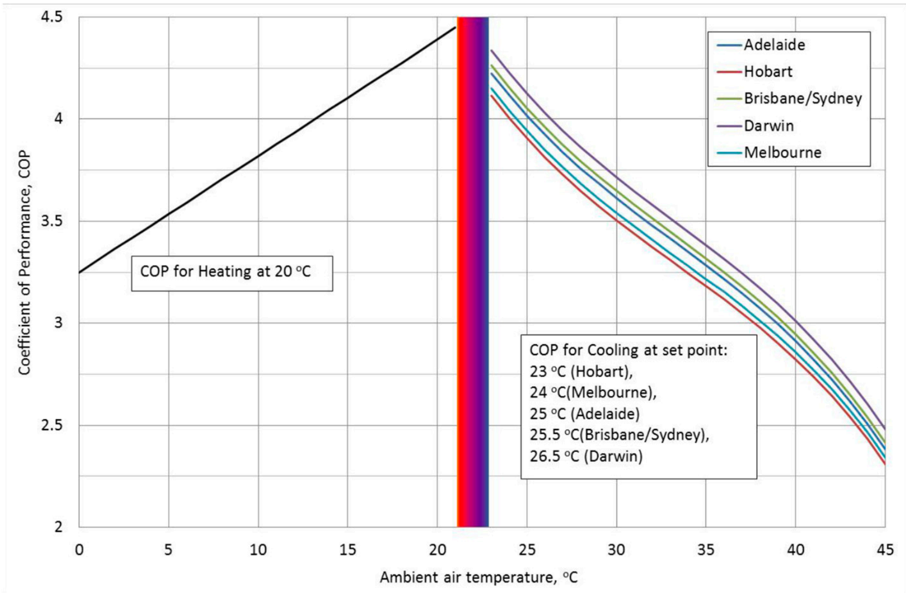

Figure 7. Coefficient of performance (COP) for Australian cities (after [27]).

The air conditioning systems were assumed to be packaged split systems which have an outdoor unit and an indoor unit connected to a ducted system. The COP captures all the electrical energy of the unit. Ventilation is not required in Australian homes and fan energy is negligible in this study. The power consumption of air-conditioning units for all simulated scenarios was calculated. To determine cooling energy consumption, the hourly ambient temperature was applied to the respective locations' COP equations (see Figure 7). Table 7 lists the latent and sensible COP equations for all cities. Equation (3) was used to determine the hourly air conditioning electrical energy consumption. The annual electrical energy consumption used for cooling was then determined for each scenario.

$$Hourly\ air\ conditioning\ electrical\ cooling\ energy\ consumption = \frac{Thermal\ load}{(Latent\ cooling\ COP + Sensible\ cooling\ COP)} \quad (3)$$

where COP: coefficient of performance.

Table 7. Latent and sensible coefficient of performance (COP) equations for all cities.

Cities	Latent Cooling COP	Sensible Cooling COP
Adelaide and Perth	-7.744×10^{-5} T^3 + 7.5128×10^{-3} T^2 − 0.26596 T + 4.3843	-7.78381×10^{-5} T^3 + 7.999×10^{-3} T^2 − 0.31338 T + 6.8555
Brisbane and Sydney	-7.744×10^{-5} T^3 + 7.5128×10^{-3} T^2 − 0.26596 T + 4.3843	-7.8869×10^{-5} T^3 + 8.0672×10^{-3} T^2 − 0.31648 T + 6.9344
Darwin	-7.744×10^{-5} T^3 + 7.5128×10^{-3} T^2 − 0.26596 T + 4.3843	-7.992×10^{-5} T^3 + 8.2121×10^{-3} T2 − 0.32298 T + 7.0952
Hobart	-7.7136×10^{-5} T^3 + 7.5892×10^{-3} T^2 − 0.27083 T + 4.4162	-7.9545×10^{-5} T^3 + 8.1222×10^{-3} T^2 − 0.3172 T + 6.8186
Melbourne	-7.7136×10^{-5} T^3 + 7.5892×10^{-3} T^2 − 0.27083 T + 4.4162	-7.8985×10^{-5} T^3 + 8.063×10^{-3} T^2 − 0.31537 T + 6.8381

COP: Coefficient of performance, T: ambient temperature.

3. Results and Discussion

3.1. Investigation of Living Wall in Australian Cities for House A

3.1.1. Annual Thermal Load and Cooling Energy

The simulation results for the total annual thermal load for the control case scenario (Condition I) for all cities are presented in Figure 8. This shows that heating is not required in Darwin, while Hobart's cooling load is insignificant compared to its heating demand. Heating is dominant in temperate climates such as Melbourne, Adelaide and Perth, while cooling is dominant in subtropical climates such as Sydney and Brisbane. Building orientation significantly affects the cooling demand in all cities, apart from Darwin, with the variation to the mean being 6.2%, 17.7%, 26.8%, 18.1%, 20.6%, 26.0% and 34.9% for Darwin, Hobart, Sydney, Melbourne, Adelaide and Perth, respectively.

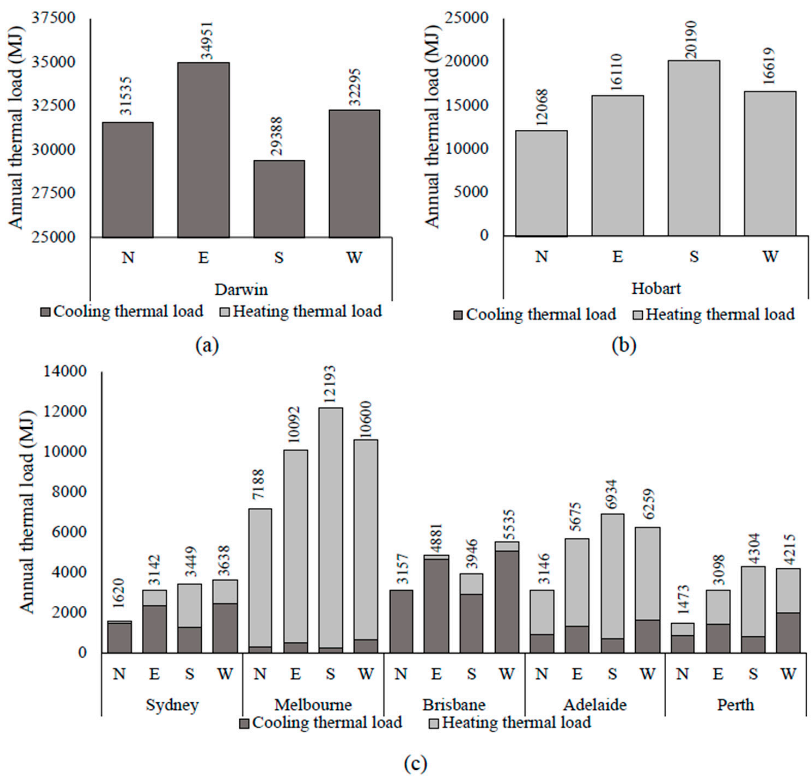

Figure 8. Annual thermal load (in MJ) for (**a**) Darwin, (**b**) Hobart, (**c**) Sydney, Melbourne, Brisbane, Adelaide and Perth for all house orientations.

For the control scenario cooling condition alone, the thermal and electrical cooling loads are presented in Figure 9. Consistent with results found in Adelaide, east and west-facing homes required higher cooling loads. These results have also confirmed that cooling loads vary according to the climate [28], with higher loads in warmer cities (Darwin, Sydney and Brisbane) and lower cooling loads in temperate cities (Melbourne, Adelaide and Perth). For Hobart, which is heating dominant, the impact of cooling was quite scattered, probably due to the small cooling load magnitude. Therefore, the results for Hobart are excluded from the following cooling analysis.

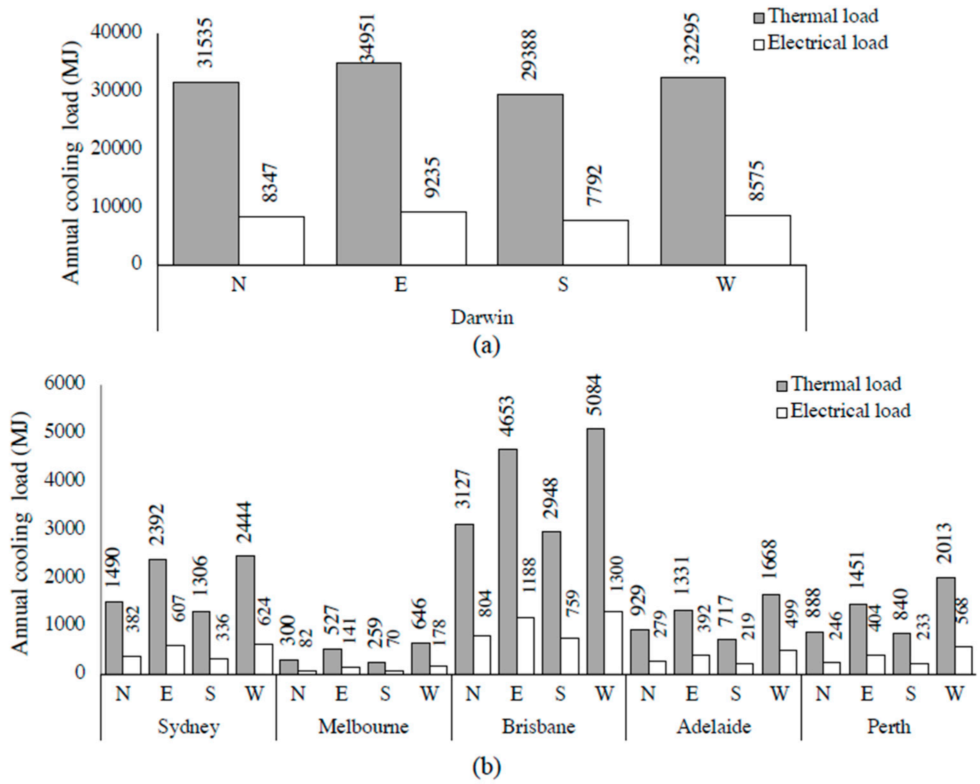

Figure 9. Annual control scenario thermal and cooling electrical load of House A in (**a**) Darwin, and (**b**) Sydney, Melbourne, Brisbane, Adelaide and Perth for all building orientations.

3.1.2. Heating Thermal Load of House A

While the focus of this investigation is concerned with cooling, it is of interest to also consider the impact of LWs on winter heating demands. The impact of LWs on the heating load of buildings is generally believed to be small [29]. For an insulated residential building (typical in Australia), this impact is expected to be even less. In order to examine this hypothesis, an analysis was conducted for House A across different climates in Australia. Since the simulated ET effect was only applied to temperatures above 25 °C, this effect was assumed to not apply in the simulated heating case.

Heating thermal loads for House A were simulated for the control scenario and the extreme case of four LWs (Condition IV). Annual heating loads for these conditions are shown in Figure 10. The LWs did not induce heating in Darwin, while heating requirements in Sydney and Brisbane were small. Adelaide, Perth and Melbourne experienced a small change in the heating load. Hobart, which is the southern-most Australian city and the one with the coolest climate, had the highest heating load and the simulation of LWs on all facades was found to dramatically increase the total heating load. This suggests that LWs may be less appropriate for cold climates.

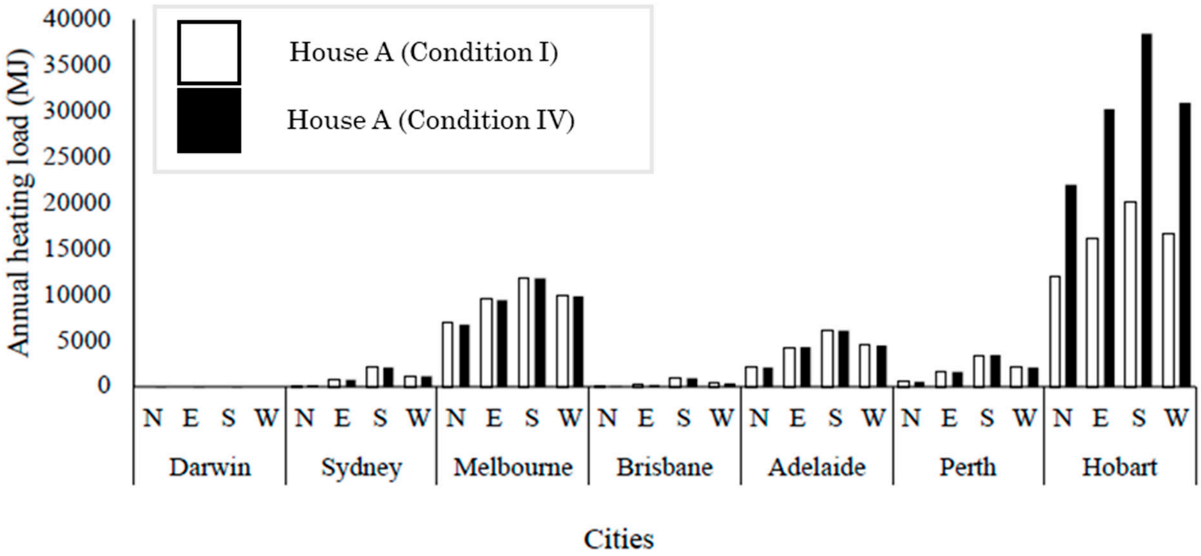

Figure 10. Annual heating loads for House A for the control scenario (Condition I) and with four living walls (Condition IV) for various house orientations in all cities.

Figure 11 presents differences in the heating load from the installation of four LWs (Condition IV), compared to the control scenario (Condition I). In most cases, the heating load decreased by less than 5%. For a north-facing house in Sydney and Brisbane, the savings were 15 and 27%, respectively, although these cities generally have a low heating load. For Perth, with a north-orientation, the corresponding saving was 10%. Given that this is for four LWs, this represents a relatively small saving. Overall, it can be concluded that LWs will yield at best a modest reduction in heating for various Australian climates requiring both heating and cooling, and may cause a significant increase in heating load for cold climates. Apart from the case of Hobart, the overall impact of LWs on heating thermal load was significantly smaller than for cooling. Therefore, heating was not investigated in further detail.

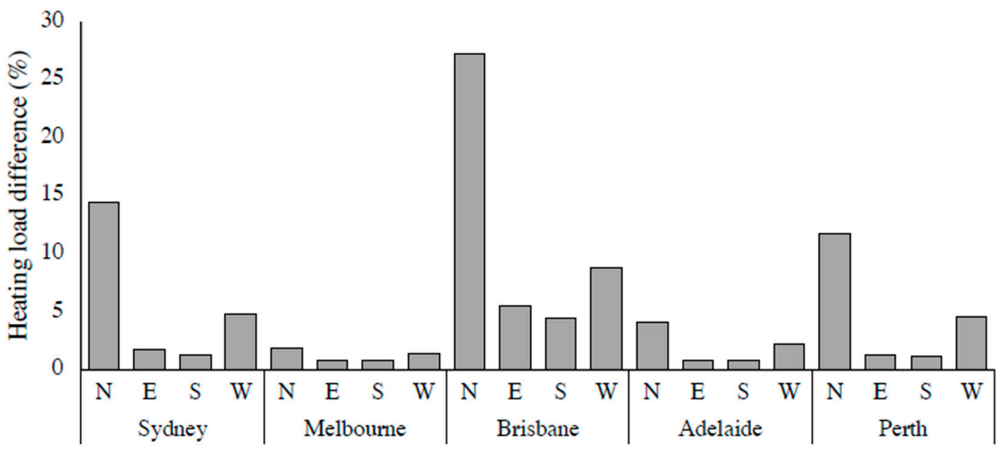

Figure 11. Decrease in annual heating thermal load for House A between Conditions 1 (control scenario) and 6 (four LWs), presented as a percentage saving, for all building orientations in Sydney, Melbourne, Brisbane, Adelaide and Perth.

3.1.3. Energy Efficiency Benefits of Light-Coloured Walls and Living Walls

The results for House A with light-coloured external walls (Condition V) are compared to the control condition (Condition I) in Table 8, for both cooling thermal and electrical loads.

Table 8. Thermal and electrical cooling load savings for light-coloured walls (Condition V) compared to the control scenario (Condition I) for Darwin, Sydney, Melbourne, Brisbane, Adelaide and Perth.

City	House Orientation	Savings Compared to Condition I	
		Thermal Load (%)	Electrical Energy (%)
Darwin	N	4.6	4.6
	E	3.6	3.6
	S	4.8	4.8
	W	4.5	4.5
Sydney	N	16.7	16.3
	E	10.5	10.3
	S	21.0	20.8
	W	13.4	13.3
Melbourne	N	18.6	19.2
	E	14.1	14.8
	S	34.6	32.9
	W	16.0	16.9
Brisbane	N	12.0	11.8
	E	8.8	8.7
	S	14.7	14.6
	W	9.5	9.4
Adelaide	N	21.3	20.3
	E	11.7	11.8
	S	13.7	14.6
	W	16.9	16.6
Perth	N	18.2	18.6
	E	13.6	14.0
	S	17.4	18.1
	W	16.6	16.8

Condition I: control scenario, N: North, E: East, S: South, W: West.

Table 9 shows the results of thermal and electrical cooling load simulations for House A with one LW (Condition III) and four LWs (Condition IV), with all walls light-coloured. In warmer tropical Darwin, changing the wall colour led to a modest 4.4% reduction in thermal load across all building orientations. Subtropical cities such as Sydney and Brisbane saw larger savings of 15.4% and 11.2%, respectively, while temperate cities such as Melbourne and Perth experienced even higher reductions (20.8% in Melbourne and 16.5% in Perth). In Sydney, Melbourne and Brisbane, south-facing walls saw the highest savings, followed by north-facing walls. The electrical energy savings closely matched the thermal load reductions, with only minor differences. A single LW had little impact in Darwin, with Sydney and Brisbane also seeing relatively small benefits. In contrast, Perth, Melbourne and Adelaide showed the highest savings at around 7%. With four LWs, there was a similar pattern but with greater savings, reaching about 20% in Perth, Melbourne and Adelaide. This reflects the ET effect, namely that drier cooling seasons benefit more from LWs.

Table 9. Annual thermal and electrical cooling load savings from one living wall (Condition III), four living walls (Condition IV), light-coloured walls (Condition V), compared as a percentage to the control scenario (Condition I) for various cities.

City	Condition	LW	House Orientation and Annual Thermal Cooling Load Savings (%)					House Orientation and Annual Electrical Cooling Load Savings (%)				
			N	**E**	**S**	**W**	**Avg.**	**N**	**E**	**S**	**W**	**Avg.**
Darwin	III	N	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
		E	0.6	0.1	0.7	0.7		0.6	0.2	0.8	0.7	
		S	0.3	0.7	0.2	0.3		0.4	0.7	0.2	0.4	
		W	0.7	0.3	0.3	0.2		0.7	0.3	0.3	0.2	
	IV	All	1.7	1.9	2.1	2.0	1.9	1.8	2.0	2.2	2.1	2.0
	V	0	4.6	3.6	4.8	4.5	4.4	4.6	3.6	4.8	4.5	4.4
Sydney	III	N	0.6	2.6	1.7	2.5	2.0	0.5	2.6	1.6	2.5	1.9
		E	0.8	0.9	4.4	2.3		0.7	0.9	4.5	2.3	
		S	1.8	2.0	1.0	3.1		1.7	2.0	0.7	3.1	
		W	0.0	1.8	4.6	1.4		−0.2	1.8	4.3	1.4	
	IV	All	5.7	2.2	12.3	8.7	7.2	5.5	2.3	12.1	8.7	7.2
	V	0	16.7	10.5	21.0	13.4	15.4	16.3	10.3	20.8	13.3	15.2
Melbourne	III	N	7.4	3.0	11.4	3.9	7.3	7.6	3.3	10.5	4.4	7.3
		E	8.8	5.7	10.2	11.5		9.6	5.8	9.2	12.3	
		S	1.4	1.1	4.8	7.2		2.0	1.4	3.1	8.4	
		W	16.8	3.6	9.5	9.7		17.3	3.8	8.2	10.1	
	IV	All	24.9	8.3	28.4	20.7	20.6	25.1	9.6	27.8	22.0	21.1
	V	0	18.6	14.1	34.6	16.0	20.8	19.2	14.8	32.9	16.9	20.9
Brisbane	III	N	0.9	2.4	2.1	1.8	1.5	1.0	2.3	2.1	1.7	1.5
		E	1.6	1.0	2.7	2.1		1.6	1.0	2.7	2.1	
		S	0.5	0.7	1.6	1.9		0.5	0.7	1.5	1.8	
		W	0.9	1.1	2.5	1.0		0.9	1.1	2.3	0.9	
	IV	All	6.0	3.3	6.4	5.6	5.3	5.9	3.3	6.3	5.6	5.3
	V	0	12.0	8.8	14.7	9.5	11.3	11.8	8.7	14.6	9.4	11.1
Adelaide	III	N	3.9	5.4	2.8	5.6	5.3	3.7	5.5	3.3	5.9	5.5
		E	10.1	3.6	6.8	6.8		9.9	3.6	8.0	6.9	
		S	6.0	4.0	1.8	6.3		5.8	4.3	2.1	6.5	
		W	5.8	5.4	2.7	7.5		5.7	5.5	3.6	7.3	
	IV	All	27.7	22.9	20.3	21.6	23.1	27.1	22.6	21.4	21.0	23.0
	V	0	21.3	11.7	13.7	16.9	15.9	20.3	11.8	14.6	16.6	15.8
Perth	III	N	9.3	3.8	7.1	3.3	5.8	9.5	3.9	7.5	3.3	6.0
		E	7.4	3.5	9.8	5.1		8.0	3.7	10.7	5.4	
		S	9.3	2.7	1.8	4.9		9.7	2.9	0.7	4.9	
		W	11.1	5.6	5.7	2.0		11.6	5.9	6.2	2.1	
	IV	All	19.7	17.6	20.6	14.5	18.1	21.0	18.5	21.9	15.0	19.1
	V	0	18.2	13.6	17.4	16.6	16.5	18.6	14.0	18.1	16.8	16.9

LW: living wall orientation, N: North, E: East, S: South, W: West, Avg: Average savings for the condition.

Comparing the effect of LWs to Condition V (all walls light-coloured) reveals a similar trend across climates. In Darwin, light-coloured walls save much more energy than four LWs, while Sydney and Brisbane also favour light-coloured walls, although the difference is smaller. In Perth, Melbourne and Adelaide, the savings are nearly the same, emphasizing the importance of the effect of ET in drier climates where LWs deliver the greatest impact. The effect of the orientation of a single LW varied with climate. In consistently hot Darwin, savings varied slightly, while in Sydney and Brisbane, there was a greater variation. However, Perth, Melbourne and Adelaide see the largest differences. In all cities, LWs on the south-facing walls delivered the least benefit, while the performance on other faces depended on building orientation. This shows that the best LW placement must consider both the wall and building orientations.

3.1.4. Shading vs. Evapotranspiration

The previous analysis of light-coloured and living walls suggests that ET plays a key role in energy savings, based on results for Adelaide's Mediterranean climate. To examine this effect across different climates, additional simulations were conducted under Condition II (dry LWs) and this was compared to Condition IV. Table 10 shows the energy savings for both conditions relative to the control scenario, with the ratio of the two conditions representing the ET effect.

Table 10. Annual thermal cooling load savings for shading from four dry living walls (Condition II) and shading and ET from four living walls (Condition IV), compared to the control scenario (Condition I).

City	House Orientation	Annual Cooling TL Savings (%)		Proportion of Savings as ET (%)
		Shading (Condition II)	Shading + ET (Condition IV)	
Darwin	N	1.0	1.7	42.4
	E	0.6	1.9	70.5
	S	1.1	2.1	49.0
	W	1.1	2.0	48.0
Sydney	N	3.9	5.7	31.2
	E	2.0	2.2	7.4
	S	6.8	12.3	44.3
	W	3.9	8.7	55.3
Melbourne	N	18.1	24.9	27.4
	E	8.3	8.3	0.0
	S	14.2	28.4	49.9
	W	12.1	20.7	41.4
Brisbane	N	3.5	6.0	41.3
	E	2.1	3.3	35.9
	S	4.9	6.4	24.3
	W	4.0	5.6	28.2

Table 10. *Cont.*

City	House Orientation	Annual Cooling TL Savings (%)		Proportion of Savings as ET (%)
		Shading (Condition II)	Shading + ET (Condition IV)	
Adelaide	N	9.3	27.7	66.4
	E	5.9	22.9	74.4
	S	6.9	20.3	65.9
	W	7.5	21.6	65.3
Perth	N	9.9	19.7	49.8
	E	7.6	17.6	56.9
	S	14.5	20.6	29.5
	W	7.2	14.5	50.6

TL: thermal load, ET: evapotranspiration, N: North, E: East, S: South, W: West.

In Darwin, the ET effect accounted for half of the total benefit, although the overall savings were small. In Sydney and Brisbane, shading was more important, but the variation was larger. In Melbourne and Perth, the ET effect contributed 0–50% and 30–57% of the benefit, respectively. Adelaide, with its dry climate, showed the highest ET effect, at 65–74%. The relative importance of ET is linked to the effect of insulated walls, which reduce the impact of shading. The results confirm that the ET effect was more prominent in drier climates and varied with wall orientation.

3.2. Investigation of the Living Wall for a Typical Adelaide House

The thermal and electrical loads for House B in Adelaide were considered for four different conditions. These were Condition I (control scenario, without LWs), Condition II (four dry LWs), Condition III (single LW) and Condition IV (four LWs). House B represents a more typical modern house design, meeting the NatHERS 6-star rating requirement. With more windows, a larger floor to wall ratio and medium-coloured external walls and roof, it is expected that the impact of LWs will be less than for the idealised House A.

3.2.1. Condition I: No Living Wall (Control Condition)

The effect of simply varying the house orientation on annual thermal load and annual electrical cooling energy are presented in Table 11. These results were used as a baseline to calculate the relative savings for the other simulated conditions.

Table 11. Annual thermal loads and electrical cooling loads for House B for Condition I (control scenario) with no LWs.

House Orientation	Cooling Thermal Load (MJ/annum)	Heating Thermal Load (MJ/annum)	Total Thermal Load (MJ/annum)	Cooling/Total Thermal Load (%)	Cooling Electrical Energy (MJ/annum)
North	8449.4	7761.7	16,211.1	52.1	2452.7
East	7082.4	8751.2	15,833.7	44.7	2093.2
South	9209.7	8240.7	17,450.3	52.8	2678.8
West	7397.6	7500.6	14,898.2	49.7	2178.3

For House B, cooling and heating demand accounted for an almost equivalent percentage of annual thermal load. Compared to House A, cooling loads consumed a larger proportion of the total load. Furthermore, in contrast to House A, the total thermal load simulated for House B showed that the optimum house orientation was west-facing. This is consistent with other studies [30] and may be due to the varied and more complex distribution of windows and the location of zones in House B. Window location will affect the time of solar gain and this will in turn affect the optimal orientation. The impact of orientation on House B's total thermal load varied between 6 and 15%, while its impact on thermal cooling varied between 4 and 23%.

3.2.2. Living Wall Impact

Under Condition III, House B was simulated with one LW on its facade. Table 12 presents the thermal and electrical cooling load savings with respect to the corresponding control scenario with the same house orientation (Condition I). The results indicate that a single Living Wall (LW) had minimal impact on House B's thermal and electrical cooling loads, reducing them by less than 1%. The building orientation and LW placement slightly affected the savings, but overall, the effects of these also remained small. In contrast, House A showed a typical saving of 10.1%, due to idealized assumptions that exaggerated the effect of the LW. Realistically, a single LW offers small savings for residential buildings. When four LWs were used, House B's annual cooling loads decreased by only 0.7–2.1%. House A, however, showed thermal cooling load savings about 10 times greater than House B. This suggests that in Adelaide, LWs provide limited energy benefits. While other house designs might see improved results, significant savings are unlikely.

Table 12. Thermal and electrical cooling load differences for House B with one living wall (Condition III) with the control scenario (Condition I) for all possible living wall and house orientation combinations.

		Thermal Cooling Load Difference from Condition I (%)				Electrical Cooling Load Difference from Condition I (%)			
		House Orientation				House Orientation			
		N	E	S	W	N	E	S	W
LW orientation	N	0.1	0.4	0.0	0.4	0.0	0.3	0.0	0.4
	E	1.1	1.0	0.9	0.2	1.0	1.0	0.9	0.2
	S	−0.6	0.9	0.5	0.8	−0.5	0.8	0.5	0.8
	W	0.9	0.4	−0.4	0.0	0.8	0.4	−0.3	0.0

LW: living wall, Condition I: control scenario, N: North, E: East, S: South, W: West.

3.2.3. Shading vs. Evapotranspiration

Table 13 compares shading only (Condition II with four dry LWs) with shading plus ET (Condition IV with four LWs) on House B's thermal cooling loads, relative to the control condition. The analysis showed that the LWs provided minimal to no shading benefits to the house. Instead, except for the west-orientation, installation of LWs increased the thermal load by 0.3–1%. Consequently, all savings are derived from the impact of the ET effect. This lends further support to the argument that LWs are more beneficial in dry climates but suggests that the benefits are likely to be small.

Table 13. Impact of shading and ET on annual thermal cooling load.

House Orientation	Thermal Cooling Load Difference from Condition I (%)		Proportion of (Condition IV) Savings as ET (%)
	Shading (Condition II)	Shading + ET (Condition IV)	
North	−1.0	0.9	100%
East	−0.3	2.1	100%
South	−0.3	1.4	100%
West	0.1	0.7	90%

ET: evapotranspiration, Condition I: control scenario, Shading: Condition II with four dry living walls, Shading + ET: Condition IV with four living walls.

4. Conclusions

Increasing the ratio of vegetated to non-vegetated spaces in our cities is an important way of mitigating the urban heat island effect. Nature-based solutions, including living walls, are therefore an essential component of next-generation urban forms because they can reduce temperatures in highly urbanised regions. They also bring additional, often intangible, environmental, social and economic benefits. The innovation of this research is that it examined the impact of LWs on modern, energy-efficient residential buildings across Australia's major cities, each with different climates. Additionally, the methodology developed to approximate the ET effect using the wet-bulb effectiveness simplifies complex thermal and moisture dynamics while maintaining accuracy. The methodology developed in this study was novel, using readily available modelling software to separate the thermal benefits of living walls to study the impact of evapotranspiration versus other factors such as shading and thermal mass. It was found that LWs provide the most cooling in warm, dry climates such as Melbourne, Perth and Adelaide, with negligible benefits in tropical climates such as Darwin. In temperate climates, living walls had little effect on heating, but in cold climates, heating demand increased. For homes with insulated walls, which are common in modern construction, the evapotranspiration effect becomes the main way living walls reduce cooling loads, which explains their greater impact in drier climates. This is an important finding that should guide future research directions. While an idealized house model showed potential cooling savings of 10–16%, applying living walls to a typical modern house reduced savings to under 1% for a single living wall. It was found that the benefit of living walls was comparable to or less than simpler, lower-cost passive design strategies such as changing building orientation or using light-coloured walls. This study also provides practical insights into the energy efficiency benefits of living walls compared to simpler passive design strategies, such as light-coloured walls or building orientation, which is an innovative contribution to the field.

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