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Impact of climate change on energy performance and energy conservation measures effectiveness in Australian office buildings

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A R T I C L E I N F O

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A B S T R A C T

The substantial energy consumption and carbon footprint of office buildings requires effective energy conservation measures (ECMs) in their design. However, climate change is expected to impact building performance and influence the effectiveness of ECMs. This paper examined the impact of climate change on office buildings in ten Australian cities, representing diverse climatic conditions. Energy simulations were conducted using Grasshopper with Ladybug tools in Rhino for a 10-storey office building, followed by a sensitivity analysis to evaluate the effectiveness of ECMs under global warming. Results revealed significant increases in cooling demands, particularly in warmer regions, with projected rises of up to 38 % under the SSP585_2080 scenario. Heating demand is expected to decrease by 48–81 % for all cases. Climate change may shift regions like Hobart from heating-dominated to cooling-oriented. Building greenhouse gas (GHG) emissions are projected to be reduced by up to 70 % by 2080 due to electricity decarbonization. Sensitivity analysis underscores the importance of solar control measures and internal heat gains in hot regions like Darwin, where their impact will be amplified by climate change. However, in regions like Hobart, where significant climatic transitions are expected by 2080, the effectiveness of ECMs becomes complex due to trade-offs between heating and cooling needs. Effective ECMs currently favor solar gain but may shift to solar control in the future, emphasizing the need for a life cycle perspective and flexible ECMs to ensure long-term efficiency. This research offers new knowledge about potential shifts in building energy demand and effective ECMs under global warming that can be utilized by architects, engineers, and policymakers.

1. Introduction

Climate change presents a significant challenge to the built environment, manifesting through erratic weather patterns and frequent extreme events [1,2]. These intensified events place greater strain on energy systems, potentially leading to power outages and further exacerbating global warming [1]. Research has demonstrated that rising temperatures will amplify cooling needs in warmer regions while altering heating requirements in traditionally cooler climates [3,4].

Australia is experiencing severe impacts of global warming, including heatwaves and heavy rainfall. The surrounding oceans have warmed by over 1 °C, while the average temperature has increased by approximately 1.47 °C since 1910 [5]. These changes not only directly affect building energy loads and structures, but also jeopardize human health and productivity [6–8].

While numerous studies have investigated future building thermal performance [8–12], the body of research specific to the Australian context remains limited [13–18]. These studies mainly emphasize on the impact of climate change on energy variations [17], building optimization [13], retrofitting [18]. However, they often fail to capture the variation in greenhouse gas (GHG) emissions across different climate zones, which directly contribute to global warming.

Furthermore, addressing climate change in the built environment necessitates both mitigation and adaptation strategies [19,20]. Mitigation efforts focus on reducing GHG emissions through more efficient building design, while adaptation aims to prepare for present and future conditions. Recent research has highlighted the need for energy conservation measures (ECMs) in building design and operation under global warming [8,12]. However, there is limited research on how climate change will affect the long-term viability of current ECMs.

Understanding these impacts is essential for decarbonizing the building sector and achieving the carbon-neutral building stock. This paper addresses the identified knowledge gap by examining office building energy demand dynamics, GHG emissions, and ECM effectiveness under global warming across Australia. The findings of this

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Abbreviations:

ECMs	Energy Conservation Measures
GHG	Greenhouse Gas
HVAC	Heating, Ventilation, and Air Conditioning
SSP	Shared Socioeconomic Pathways
RCP	Representative Concentration Pathway
SRES	Special Report on Emissions Scenarios
GCMs	General Circulation Models
CLT	Cross-Laminated Timber
NT	Near Term
MT	Mid Term
LT	Long Term
UHI	Urban Heat Island
HDD	Heating Degree Days
CDD	Cooling Degree Days
NABERS	National Australian Built Environment Rating System
EPW	EnergyPlus Weather
EUI	Energy Use Intensity
SHGC	Solar Heat Gain Coefficient
WWR	Window-to-Wall Ratio
IHG	Internal Heat Gains
UAE	United Arab Emirates
AusLCI	Australian Life Cycle Inventory
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
COP	Coefficient of Performance
EER	Energy Efficiency Ratio

research have significant implications for multiple stakeholders. The results will inform architects in developing future-proof building designs and assist engineers in selecting climate-resilient ECMs. Furthermore, this study will provide guidelines for policymakers to develop climate-responsive building codes and support researchers in investigating diverse ECMs for different building types in Australia and beyond.

2. Literature review

Research into the effects of global warming on building thermal performance has received increasing attention worldwide [11]. This body of work primarily examines 1) the creation of future weather projections; 2) the influence of global warming on heating, cooling, and peak energy [4]; and 3) strategies to mitigate these impacts through design, optimization, and retrofitting.

To create future weather files, general circulation models (GCMs) are utilized to predict climate variations [6,21]. These models, however, are limited by their coarse resolution, necessitating downscaling for precise building simulations [22]. The morphing method leverages existing weather data and climate models [23], which have been widely used in later studies. Guan [24] reviewed four methods for generating future weather files in 2009. Moazami et al. [2] discussed the advantages and drawbacks of statistical and dynamic methods.

Given the complexity, time-consuming nature, and expertise required to create weather files, several tools have been developed to streamline this process. These include CCWorldWeatherGen, Weathershift, Meteonorm, and the more recent *Future Weather Generator*. Jentsch et al. [25] presented the most widely used tool: CCWorldWeatherGen, which employs morphing to generate files for the A2 emissions scenario. Weathershift utilizes the morphing approach to create future files for 259 cities worldwide [26]. The Meteonorm serves as a climate database and is capable of generating weather files for any location by employing stochastic generation and interpolation algorithms for typical years [27]. Addressing the limitations of outdated models and the dependency on commercial software, Rodrigues et al. [28] introduced the open-source *Future Weather Generator*, capable of producing hourly weather files for 2050 and 2080 using the latest shared socioeconomic pathway (SSP) scenarios.

Numerous studies worldwide have discussed the effects of global warming on building thermal performance. Table A1 summarizes the last three years of research. Jalali et al. [29] explored residential building thermal performance under representative concentration pathway (RCP) in New Zealand. This impact could be both negative (warmer zones) and positive (colder zones). D'Agostino et al. [30] analyzed the energy balance of nearly zero energy buildings under global warming in eight European locations.

The majority of these studies concentrated on developed regions, such as Europe (Table A1). Moreover, some studies have investigated cross-country comparisons, as climate, building regulations and thermal characteristics differ across countries [22,31–38]. For example, Khawaja and Memon [34] evaluated the integration of phase change material into the envelope to investigate the cooling energy-saving potential in 13 Köppen climate zones.

These studies have been performed both at individual building and district scales. For individual buildings, various building prototypes, predominantly those from ASHRAE, have been utilized for investigation [2,6,39,40]. At the district scale, Deng et al. [41] evaluated the thermal consumption of two Geneva neighborhoods under four SSP scenarios. Mutschler et al. [42] factored in population growth and increased cooling equipment to assess national heating and cooling needs under global warming.

However, the accuracy of these studies depends greatly on the climate data used. Studies based on historical weather data or outdated climate scenarios may not accurately reflect future conditions. Yang et al. [22] reported relatively small projected decreases in future heating demand in Swedish cities under the RCP scenarios compared to previous studies using the SRES scenarios. Most recent studies (Table A1) have relied on RCP scenarios introduced in 2014, with some even referencing SRES from 2000. However, these scenarios now deviate from current patterns and cannot accurately represent future pathways. This underscores the importance of using the latest model/scenarios to ensure alignment with current climate trajectories and trends.

Sensitivity analyses have been utilized to assess the effect of ECMs on reducing building energy under current weather conditions [43–45]. For example, Chen et al. [44] discussed the relative significance of passive ECMs, such as building orientation, envelope, windows, shading, and airtightness. Qin and Pan [45] concluded that occupant behavior has the most significant effect. However, climate change adds a layer of complexity to the implementation of ECMs as climate parameters alter with global warming. Much of the existing research on ECMs focuses on their effectiveness under past weather conditions. Limited research is available on how climate change affects the long-term effectiveness of

ECMs.

Retrofit scenarios and uncertainty under climate change have been explored in Refs. [35,46–52]. Radhi [48] investigated the ECM measures on energy consumption under different scenarios in the UAE, indicating that improving insulation and thermal mass was effective and reduced 13 % and 15 % of GHG emissions. Huang and Hwang [52] investigated multiple passive measures, and showed that no individual adaptation measure was able to curb the cooling energy at current levels. Existing studies typically focus on the ability of ECMs to reduce energy or curb energy increases under climate change. However, the changing effectiveness of ECMs under global warming remains unclear. Whether their impact will be more pronounced, diminished, or remain constant will significantly influence the selection of future-oriented ECM.

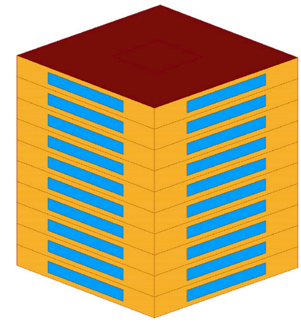
This investigation aims to bridge the gap by assessing future building thermal performance and evaluating the effectiveness of various ECMs under global warming. Specifically, the research aims to answer: 1) How do the latest climate change projections and scenarios affect energy performance and GHG emissions across Australia? 2) How effective are different ECMs in reducing energy consumption over time in different climate zones, and how should they be chosen?

The contribution of this study lies in investigating how office building thermal performance changes under global warming in Australia. Through this comprehensive investigation, the study explores potential pattern changes across Australia. The findings will inform building design and code development to better adapt to global warming. Furthermore, it adds to the existing body of knowledge by quantifying the effectiveness of implementing ECMs for both current and future periods. This approach enables the assessment of the suitability and long-term viability of these measures in diverse climatic contexts. This will inform decision-makers in selecting and implementing climate change resilient ECMs, thereby providing guidance for sustainable building practices in Australia and globally.

3. Material and methods

Australia employs its own climate zone classification system, which ranges from Zone 1 (hot humid summer, warm winter) to Zone 8 (alpine). This system is used alongside international standards such as the ASHRAE climate zones in this study. Ten cities (Table 1) were selected to capture diverse climate conditions, spanning from tropical to cold regions and from coastal to inland areas. These representative sites provide a broad basis for understanding the future office buildings energy performance in various climatic conditions across Australia.

Table 2
Characteristics of baseline office building model [18,57–59].

Parameters	Values
Analyzed building	
Geometry (m)	31.6 × 31.6
Total floor area (m^2)	9985.6
Storey	10
Floor-to-floor height (m)	3.6
Occupant density (Person/m^2)	1/10
Equipment load (W/m^2)	11
Lighting load (W/m^2)	4.5
Building operations schedule	Estimating NABERS ratings [58]
Window-to-Wall Ratio (WWR)	30 %
Heating, Ventilation, and Air Conditioning (HVAC)	VAV with PFP Boxes
Heating setpoint(°C)	20
Cooling setpoint(°C)	24

A 10-storey office building was selected to represent the typical central business district office building. The building template was developed in line with the Australian Building Codes Board guidelines [16] and has been extensively studied in Refs. [16,18,53]. The geometrical details and assumptions are displayed in Table 2. The building was modeled in Rhino, with energy simulations conducted through Grasshopper with Ladybug tools (EnergyPlus engine). Building properties were assigned referring 'Construction Set by Climate' component for thermal characteristics of the envelope (Table 1). The Ladybug component provides pre-defined building envelope configurations tailored to each climate zone. The primary structural system utilizes cross-laminated timber (CLT), selected for its advantageous characteristics including structural integrity, low emissions, and efficient prefabrication potential [54,55]. Its properties have led to its increasing adoption in building practice [56]. The building envelope

Table 1
Australian cities and their building envelope thermal properties.

City	Region	Climate zones		U-value (W/(m^2·K))			SHGC
		Australia	ASHRAE	Exterior Wall	Roof	Window	Window
Darwin	Northern Territory	1	1B	0.46	0.15	2.86	0.25
Townsville	Queensland	1	1A	0.46	0.15	2.86	0.25
Brisbane	Queensland	2	2A	0.46	0.15	2.12	0.25
Alice Springs	Northern Territory	3	2B	0.46	0.15	2.12	0.25
Perth	Western Australia	5	3A	0.46	0.15	1.89	0.25
Adelaide	South Australia	5	3A	0.46	0.15	1.89	0.25
Sydney	New South Wales	5	3A	0.46	0.15	1.89	0.25
Melbourne	Victoria	6	3C	0.46	0.15	1.89	0.25
Canberra	Australian Capital Territory	7	4A	0.33	0.12	1.78	0.36
Hobart	Tasmania	7	4A	0.33	0.12	1.78	0.36

assembly comprises multiple layers with specific thermal properties. The external wall construction consists of a 160 mm CLT panel (λ = 0.13 W/(m·K)) as the primary structural element, supplemented by exterior cladding and interior gypsum board finishing layers. Glass wool insulation (λ = 0.04 W/(m·K)) of varying thicknesses are incorporated to achieve the climate zone-specific thermal performance requirements. This study focuses on cross-climate zone comparisons rather than specific regional analyses. By employing standardized construction sets for thermal properties across different climate zones, the research aims to achieve equivalent energy efficiency. Such approach ensures that observed variations are primarily due to climate change, rather than disparities in building thermal characteristics.

For the baseline weather data, the Ladybug EPW map was utilized. To generate future climate data, the open-source *Future Weather Generator* tool was employed [28], which created weather files for 2050 and 2080 under the SSP245 (intermediate emissions) and SSP585 (very high emissions) scenario. These scenarios provide valuable insights into potential future climatic conditions and have been widely used in Refs. [28,41,60–64]. SSP245 represents a likely scenario based on current policies [65], and was used as the potential pathway for future weather in Singapore [64]. The SSP585 scenario, although not the most plausible [62], was studied due to its importance in examining the largest potential effect [66].

The analysis focuses on three key indicators: energy demand

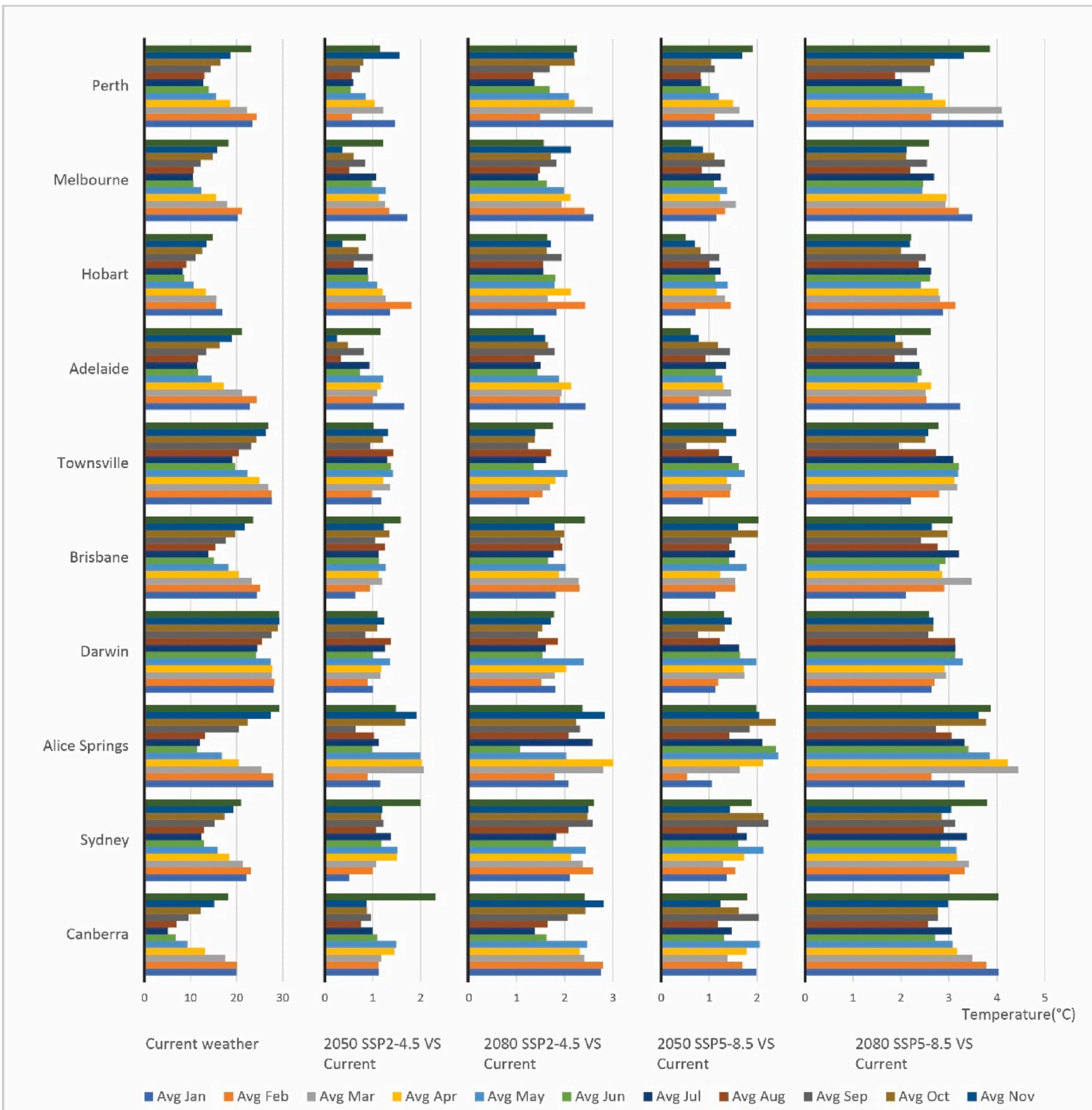


Fig. 1. Average monthly dry bulb temperature under baseline and future periods.

dynamics, GHG emissions, and ECM effectiveness. The computational methods include degree-day calculations and hourly simulations. Heating degree days (HDD) and cooling degree days (CDD) are computed using a base temperature of 18 °C [39,67–70]. The calculation involves dividing the hourly temperature variance between the base and outdoor temperatures by 24.

To investigate the effectiveness of ECMs under climate change, a sensitivity analysis was conducted. Various ECMs were considered, including building thermal characteristics (wall and roof U-values, solar absorptance, window properties), occupant behavior (setpoints), internal heat gains (lighting and equipment loads), and system efficiency (sensible heat recovery). Two representative cities, Darwin and Hobart, were selected for the sensitivity analysis, representing distinct trends in energy changes.

4. Results and discussions

4.1. Climate data

Fig. 1 reveals a clear increasing trend in temperatures, with monthly

Table 3
Climate parameter comparison between the baseline and future scenarios.

Location	HDD 18	CDD 18	Dry-bulb temperature			Relative humidity	Wind speed	Direct Normal Radiation	Diffuse Horizontal Radiation
			Average	Min	Max	%	m/s	Wh/m^2	Wh/m^2
Canberra									
Baseline	2298	387	12.80	−6.2	39.8	69.9	2.1	202.5	71.8
SSP245_2050	1994	517	13.99	−5.6	40.7	68.9	2.2	295.4	66.5
SSP245_2080	1740	651	15.06	−5.8	43	68.9	2.1	296.5	66.4
SSP585_2050	1864	547	14.43	−5.4	42.7	68.9	2.2	294.8	67.2
SSP585_2080	1519	776	16.01	−3.8	44.5	68.7	2.1	297.9	66.2
Sydney									
Baseline	798	656	17.64	4	42.2	70.6	3.2	183.5	69.2
SSP245_2050	593	902	18.88	5	44.2	69.5	3.2	232.6	73.3
SSP245_2080	465	1156	19.93	5.6	45.2	69.7	3.2	230.0	73.7
SSP585_2050	510	997	19.36	5.3	43	69.4	3.3	226.4	74.7
SSP585_2080	354	1366	20.81	6.8	46.1	68.9	3.2	233.8	72.7
Alice Springs									
Baseline	856	2007	21.19	−2.5	42	40.9	2.3	301.1	57.0
SSP245_2050	705	2375	22.61	−1.8	43.9	40.0	2.3	380.5	62.4
SSP245_2080	610	2587	23.46	−2.2	44.3	39.9	2.3	382.4	62.3
SSP585_2050	630	2451	23.02	−1.3	44.1	38.7	2.3	386.2	61.2
SSP585_2080	478	2917	24.72	0.9	46.2	40.0	2.3	372.7	64.3
Darwin									
Baseline	2	3411	27.34	15.5	35.6	69.5	3.3	225.8	81.6
SSP245_2050	1	3822	28.47	16.5	36.8	69.2	3.4	297.4	86.9
SSP245_2080	0	4047	29.09	17.1	37.8	68.9	3.4	301.2	85.9
SSP585_2050	0	3929	28.77	17	37.7	68.5	3.4	307.0	84.6
SSP585_2080	0	4454	30.21	18.8	38.6	69.3	3.4	293.5	88.0
Brisbane									
Baseline	482	1153	19.87	2.1	32.8	71.2	3.5	209.9	70.1
SSP245_2050	361	1457	21.03	3	35	70.5	3.4	237.7	82.5
SSP245_2080	296	1690	21.85	4.2	35.9	71.8	3.5	234.0	82.9
SSP585_2050	326	1566	21.43	3.6	35.5	70.9	3.5	242.5	80.9
SSP585_2080	213	1924	22.72	5.3	36.5	71.3	3.4	235.8	82.4
Townsville									
Baseline	100	2311	24.08	5.3	33.8	69.0	3.0	215.7	89.2
SSP245_2050	65	2727	25.32	6.5	34.8	67.6	3.1	338.4	84.3
SSP245_2080	54	2837	25.65	7.3	35	70.5	3.0	324.6	87.2
SSP585_2050	63	2758	25.41	6.8	34.8	68.2	3.1	339.6	83.9
SSP585_2080	30	3256	26.86	8.7	36.2	68.9	3.1	329.5	86.2
Adelaide									
Baseline	1181	818	17.05	2.1	44	59.9	3.1	210.3	70.9
SSP245_2050	1007	975	17.95	2.9	44.8	59.4	3.1	256.0	69.4
SSP245_2080	835	1108	18.79	3.2	45.8	59.5	3.0	258.3	69.2
SSP585_2050	936	986	18.18	2.7	44.9	59.1	3.1	259.7	68.8
SSP585_2080	716	1229	19.45	4.2	46.8	59.6	3.1	261.8	68.3
Hobart									
Baseline	2144	124	12.48	0.4	38.1	69.2	3.5	158.3	65.5
SSP245_2050	1840	186	13.49	1.3	40.6	68.8	3.6	238.0	68.3
SSP245_2080	1601	235	14.28	1.9	40.7	68.4	3.7	246.1	67.5
SSP585_2050	1814	177	13.53	1.5	38.9	68.6	3.7	244.7	67.6
SSP585_2080	1385	293	15.03	2.9	41.7	68.5	3.6	246.3	67.3
Melbourne									
Baseline	1506	400	15.00	2.5	38.1	68.1	3.9	156.6	67.9
SSP245_2050	1263	532	16.03	3	40.6	66.8	4.0	174.1	74.6
SSP245_2080	1063	649	16.90	3.2	42.6	66.1	4.0	184.8	73.0
SSP585_2050	1216	528	16.15	2.7	40.5	67.1	3.9	176.0	74.6
SSP585_2080	885	742	17.65	4.3	42.7	66.6	3.9	181.3	73.4
Perth									
Baseline	911	916	18.05	1.2	40.7	63.9	3.0	240.0	61.0
SSP245_2050	765	1108	18.97	1.7	42	63.4	3.0	257.8	72.6
SSP245_2080	606	1345	20.05	1.7	43.8	61.8	3.0	258.6	73.0
SSP585_2050	708	1193	19.36	1.2	42.8	62.7	3.1	254.2	73.4
SSP585_2080	511	1591	20.99	1.9	44.8	61.6	3.0	262.5	71.8

temperature rises ranging from 1 to 3 °C in 2050 and 1–5 °C in 2080 across Australia. Notably, cities such as Canberra, Sydney, and Alice Springs experienced significant surges in average yearly temperatures, exceeding 3 °C by 2080 under the SSP585 scenario compared to the baseline. The projected temperature increases in Australia align with global warming trends but show regional variations. Rodrigues et al. [62] found that Tabriz, Iran, could see average temperature increases of 4.3 °C by 2050 and 7.8 °C by 2080. The discrepancies between these projections and those for Australian cities may be attributed to geographical differences, such as Australia's oceanic surroundings, which tend to moderate temperature extremes. Coastal cities (e.g., Adelaide, Brisbane) and tropical cities (e.g., Darwin, Townsville) exhibit smaller temperature variations compared to inland cities (e.g., Canberra, Alice Springs). These variations can be further influenced by differences in baseline weather periods and local climatic conditions.

Darwin's average monthly temperature in winter (June and July) remains around 27 °C, with the average yearly temperature reaching 30.21 °C in SSP585_2080. This shift towards a generally warmer climate highlights the need for active and advanced cooling technologies, as passive cooling strategies may become inefficient. It can also be seen that the increases in temperature exhibit variability across different cities and months. For instance, Brisbane and Sydney show a more uniform temperature increase throughout the year. In cities like Perth, Canberra, and Alice Springs, the temperature rise is more pronounced during the cooling periods (i.e., January and December). For Canberra, the average temperature in January is projected to rise from 19.97 °C to 21.10 °C (SSP245_2050) and 24.00 °C (SSP585_2080).

Cities like Canberra, Sydney, Alice Springs, Adelaide, Hobart, Melbourne, and Perth are expected to experience peak temperatures exceeding 40 °C in the future (Table 3). This is echoed in the findings of Chen et al. [71], who reported temperature increases of more than 4 °C by 2090 under the RCP 8.5 scenario for Brisbane, Alice Springs, Canberra, Melbourne, Sydney, and Hobart. Notably, this research does not account for the urban heat island (UHI) effect, which could lead to even higher temperatures for urban office buildings. For instance, Salvati and Kolokotroni [38] reported a temperature increase of 2.4 °C due to global warming and an additional 0.5 °C rise attributed to the microclimate effect during August in London. These microclimates, coupled with extreme events, will place immense stress on HVAC systems and the electrical grid, leading to a heightened risk of power outages. This emphasizes the need for measures to mitigate and adapt to these effects.

Cities like Canberra, Hobart, and Melbourne, which currently have higher HDDs, are projected to experience significant reductions of up to 34–41 % in HDDs in SSP585_2080 (Table 3). This significant reduction in HDDs is due to global warming, which will result in milder winters and fewer days requiring heating in regions that are currently cooler. On

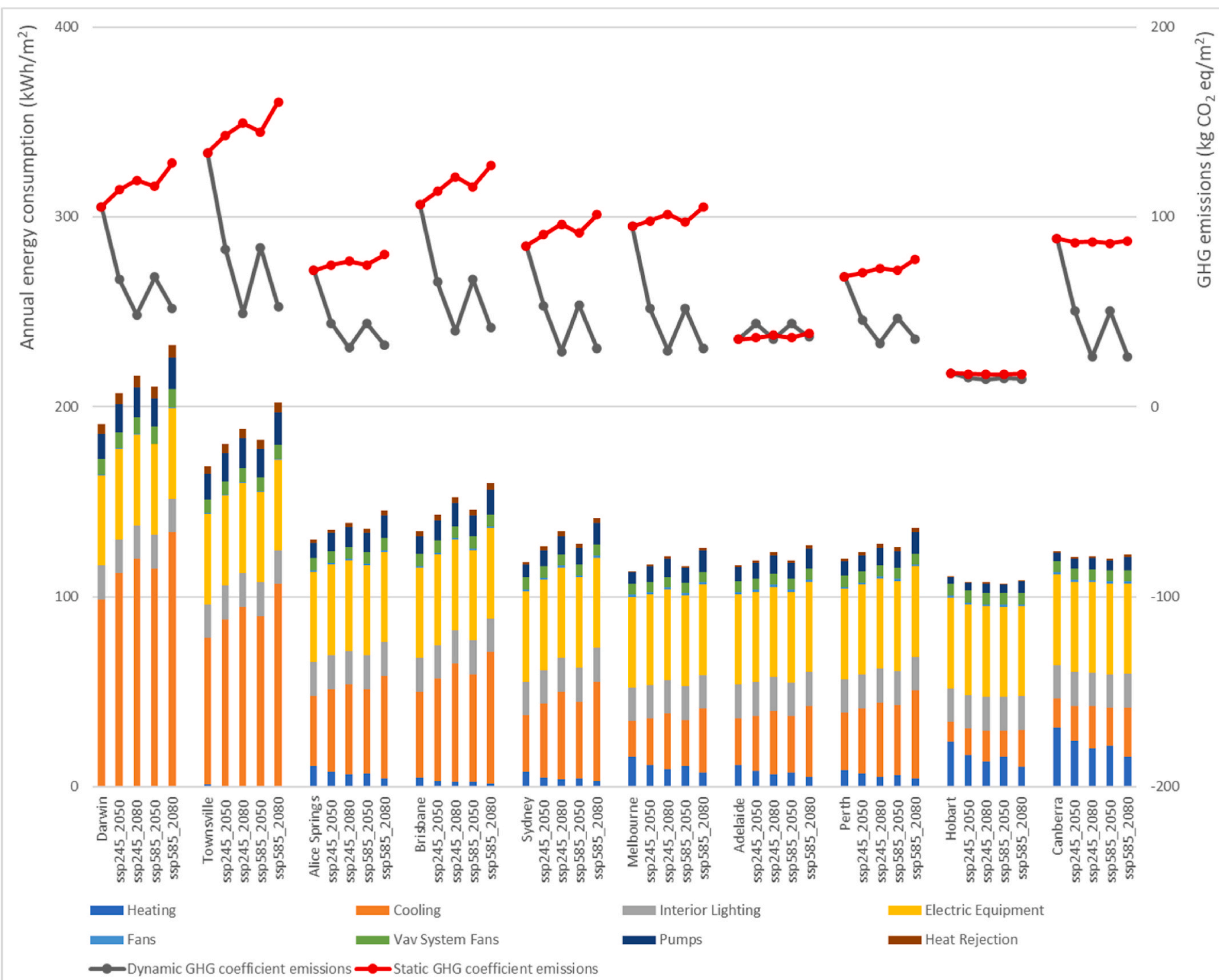


Fig. 2. Total EUI and associated GHG emissions for office buildings in baseline, 2050 and 2080.

the other hand, cities like Darwin, Townsville, and Alice Springs, which have relatively low HDDs and high CDDs currently, are expected to face substantial increases in cooling, with CDD rising by 31 %, 41 % and 45 %, respectively. Table 3 shows an increase in radiation under future periods, except for a slight decrease in diffuse horizontal radiation for Canberra and Adelaide. Elevated solar radiation levels can boost photovoltaic output; however, this may also contribute to increased cooling loads if not properly managed through effective shading and window design strategies.

4.2. Building energy consumption and GHG emissions

While projected increases in CDD and temperatures indicate higher cooling energy demands, factors such as HVAC systems, occupant behavior, and humidity influence the accuracy of these projections. Fig. 2 illustrates the annual energy consumption across various climates, exhibiting a consistent rise in cooling energy use intensity (EUI) over time. To validate the simulation results, a comparison is drawn with findings from other independent studies. Daly et al. [18] reported annual total energy consumption values of approximately 150 kWh/m^2 for office buildings in Sydney, Melbourne, Canberra, and Adelaide, using similar template buildings. The present study yielded significantly lower values, ranging from 113 to 124 kWh/m^2 for the same cities. These variations in energy demands could be attributed to various factors, including the thermal resistance of the building envelope, HVAC system efficiency, occupant behavior patterns, operational schedules and internal building loads. For instance, a particularly significant difference lies in the assumptions for lighting density. This study assumes 4.5 W/m^2 in accordance with the latest National Construction Code in Australia [59]; whereas Daly et al. [18] assumed 11 W/m^2 for lighting loads. Such difference contributes to a considerable discrepancy in total EUI between the studies.

Under the SSP585_2080 scenario, cooling demands exhibit significant increases across all cities: 36–38 % in Darwin and Townsville, 51–54 % in Brisbane, Adelaide and Perth, and 75–81 % in Sydney and Melbourne, compared to the baseline. The largest relative increase is observed in Hobart, with an 85.11 % rise in cooling demand. Regarding heating energy consumption, substantial decreases are observed: about 64 % in Sydney and Brisbane, about 54–59 % in Alice Spring, Melbourne Adelaide and Hobart, and 48–50 % in Perth and Canberra. These trends broadly align with previous research examining office buildings under the A2 scenario [18], which reported heating demand reductions of 50.2 % in Canberra, 52 % in Adelaide, 43.9 % in Melbourne, and 73.1 % in Sydney. The magnitudes differ, primarily due to disparities in climate data (GCM, scenarios, base weather files), the building's thermal characteristics, and basic levels. In addition, comparisons should be made cautiously, as relative changes are linked to baseline levels (Table 4). For instance, a 35.47 kWh/m^2 increase in Darwin yields a 36.06 % cooling rise, while Hobart's 8.94 kWh/m^2 change results in an 85.11 % cooling increase. Heating demands in 2080 are expected to decrease by 35–68 % under SSP245 and 48–81 % under SSP585. The maximum absolute reduction is 11.01 kWh/m^2 (35.59 %) in Canberra for SSP245_2080 and 15.05 kWh/m^2 (48.62 %) for SSP585_2080 to the baseline.

The absolute variations in heating demand over time are more pronounced than cooling demand in colder climate areas, such as Hobart and Canberra, over time. While tropical regions exhibit larger absolute changes in cooling demand compared to cold regions, their relative changes are proportionally smaller than those observed in colder regions. This can be attributed to the relatively low baseline cooling demand in Hobart and Canberra, where small amount absolute changes in cooling can result in substantial percentage variations in energy consumption patterns. The rise in cooling needs over time is greater in colder areas compared to those in warmer areas, aligning with the findings of [22]. This disparity between absolute and relative changes underscores the importance of considering both metrics to fully understand the magnitude and proportional changes relative to baseline

Table 4
Relative and absolute changes of heating, cooling and total energy.

	Relative heating changes				Relative cooling changes				Relative total energy changes			
	SSP245_2050	SSP245_2080	SSP585_2050	SSP585_2080	SSP245_2050	SSP245_2080	SSP585_2050	SSP585_2080	SSP245_2050	SSP245_2080	SSP585_2050	SSP585_2080
Darwin	−49.22 %	−57.03 %	−53.91 %	−68.75 %	14.13 %	21.75 %	16.70 %	36.06 %	8.59 %	13.29 %	10.28 %	21.79 %
Townsville	−62.50 %	−68.06 %	−63.24 %	−81.21 %	13.68 %	22.42 %	16.06 %	38.35 %	6.98 %	11.77 %	8.27 %	20.03 %
Alice Springs	−25.86 %	−38.73 %	−37.12 %	−58.70 %	17.58 %	27.48 %	20.17 %	46.01 %	4.08 %	6.62 %	4.12 %	11.64 %
Brisbane	−34.46 %	−47.21 %	−42.14 %	−63.93 %	18.92 %	37.82 %	25.00 %	53.02 %	6.34 %	13.43 %	8.50 %	18.92 %
Sydney	−36.03 %	−49.47 %	−44.18 %	−63.55 %	29.61 %	54.33 %	35.89 %	75.98 %	6.93 %	13.53 %	8.03 %	19.41 %
Melbourne	−27.04 %	−40.67 %	−30.72 %	−54.32 %	30.16 %	55.50 %	29.87 %	81.22 %	3.01 %	6.76 %	2.30 %	10.72 %
Adelaide	−27.13 %	−43.28 %	−34.77 %	−54.74 %	17.63 %	36.32 %	20.62 %	51.75 %	2.23 %	5.88 %	2.25 %	9.15 %
Perth	−22.79 %	−40.04 %	−28.52 %	−50.59 %	14.35 %	30.01 %	22.21 %	54.41 %	2.78 %	6.35 %	4.88 %	13.49 %
Hobart	−28.62 %	−44.37 %	−33.05 %	−56.23 %	30.86 %	56.25 %	29.70 %	85.11 %	−2.39 %	−2.68 %	−3.51 %	−1.67 %
Canberra	−22.96 %	−35.59 %	−30.55 %	−48.62 %	22.04 %	45.73 %	30.54 %	68.09 %	−2.47 %	−1.88 %	−2.98 %	−1.47 %
	Absolute heating changes (kWh/m^2)				**Absolute cooling changes (kWh/m^2)**				**Absolute total energy changes (kWh/m^2)**			
	SSP245_2050	SSP245_2080	SSP585_2050	SSP585_2080	SSP245_2050	SSP245_2080	SSP585_2050	SSP585_2080	SSP245_2050	SSP245_2080	SSP585_2050	SSP585_2080
Darwin	−0.13	−0.15	−0.14	−0.18	13.90	21.40	16.42	35.47	16.40	25.37	19.63	41.60
Townsville	−0.77	−0.83	−0.77	−0.99	10.53	17.25	12.36	29.51	11.76	19.83	13.93	33.74
Alice Springs	−2.81	−4.21	−4.03	−6.37	6.48	10.14	7.44	16.97	5.31	8.62	5.36	15.16
Brisbane	−1.65	−2.26	−2.01	−3.05	8.53	17.05	11.27	23.90	8.53	18.06	11.43	25.44
Sydney	−2.80	−3.84	−3.43	−4.94	5.63	10.35	5.57	15.15	8.20	16.02	9.51	22.98
Melbourne	−4.26	−6.41	−4.85	−8.57	5.63	10.35	5.57	15.15	3.42	7.68	2.61	12.18
Adelaide	−3.06	−4.88	−3.92	−6.17	4.34	8.94	5.07	12.73	2.60	6.85	2.63	10.66
Perth	−1.99	−3.50	−2.49	−4.42	4.31	9.01	6.67	16.33	3.34	7.63	5.86	16.20
Hobart	−6.72	−10.41	−7.75	−13.19	3.24	5.91	3.12	8.94	−2.64	−2.96	−3.88	−1.85
Canberra	−7.11	−11.01	−9.46	−15.05	3.37	7.00	4.67	10.42	−3.06	−2.33	−3.68	−1.82

conditions.

As a result, the heating-to-cooling ratio will shift significantly, and all cases will transition to being cooling-dominant in future 2080 scenarios. In heating-dominated regions like Hobart, this ratio will change from 2.23 at baseline to 0.80 under SSP245_2080 and further decrease to 0.53 under SSP585 by 2080. Canberra demonstrates a similar trajectory, with the ratio declining from 2.02 (Baseline) to 0.89 (SSP245_2080) and 0.62 (SSP585_2080), respectively. This shift is consistent with a study in Belgium [72], which reported that Brussels would change from heating to cooling dominance by the 2090s.

Higher cooling demand will also drive increases in energy consumption for auxiliary HVAC components such as fans, pumps, and heat rejection systems. Under the SSP585_2080 scenario, Darwin would experience increases of 1.34 kWh/m^2 (16.17 %) in VAV system fans and 3.75 kWh/m^2 (28.71 %) in pumps energy compared to the baseline. Similarly, in Townsville, the pumps energy and heat rejection energy are projected to increase by 3.82 and 1.11 kWh/m^2 respectively under the same scenario.

The implications of climate change on total energy exhibit varying trends across different geographical locations. In colder regions, represented by climate zone 7 (Hobart and Canberra), climate change is projected to have a beneficial effect, with a net decrease of 1.88–2.68 % (SSP245_2080) and 1.47–1.67 % under SSP585_2080 scenario in total EUI. However, hot regions, such as climate zone 1 (Darwin and Townsville), are anticipated to face significant adverse impacts, experiencing an increase of 33–42 kWh/m^2 (20–22 %) under the SSP585_2080 scenario. For climate zones 2–6, varying levels of upward trends are expected, with increases ranging from 5 to 14 % (6–18 kWh/m^2) under the SSP245_2080 scenario and 9–19 % (10–25 kWh/m^2) under the SSP585_2080 scenario. These trends are consistent with a study in New Zealand [4], which indicated an increasing trend in moderate climate zones and a decreasing trend in colder climates for RCP scenarios. This highlights the complex dynamics and potential non-linear effects of global warming on energy demands, which may differ across different time horizons and emission scenarios.

Table 5 shows the findings of previous studies. These discrepancies are closely linked to factors such as building types, climate change scenarios, GCM selections, future weather generation methods, time periods, climatic regions, and building thermal characteristics. Moazami et al. [2] reported that fast-food restaurants exhibited the widest range of primary energy consumption variations, while hospitals had the smallest range. This can be attributed to the higher ventilation rates in restaurants and the more energy-intensive equipment and end-uses in hospitals. This finding is reinforced by Berardi and Jafarpur [6] and Xu et al. [39], indicating that smaller buildings are more susceptible to the impacts of global warming due to higher envelope heat loss/gain ratios compared to larger buildings. These findings emphasize the need for caution when comparing results across different building types. Furthermore, other factors also influence the magnitude of variation. Liu et al. [73] reported that the impact of variability among different GCMs surpasses the differences observed among two RCP scenarios and time periods. P.Tootkaboni et al. [74] indicated that statistical downscaling methods generally overestimated cooling loads compared to dynamical downscaling approaches, especially during August. These findings collectively emphasize the complexity of assessing future building energy performance and the need for careful consideration when comparing variations.

Fig. 2 also illustrates the building GHG emissions trends based on AusLCI data. A clear divergent trend emerges between static and dynamic electricity coefficients. With the static scenario, changes in GHG emissions would mirror total EUI variations, as all energy is sourced from electricity without trade-offs. However, for residential buildings, the trade-off between heating and cooling energy may require consideration [3]. This static scenario leads to significant increases in GHG emissions for most studies, with exceptions in cold regions showing decreases or negligible (Hobart and Canberra).

Comparisons with other studies show mixed trends. These depend on location (pattern changes), heating/cooling energy sources, and energy mix. For instance, Jafarpur and Berardi [76] reported decreasing GHG emissions trends in three Canadian cities, attributable to relatively low electricity emission factors compared to heating intensity from natural gas. This trend favors the transition from heating to cooling for emissions reduction, particularly in regions with cleaner energy sources. Similar decreasing trends were reported in Belgium [72]. However, countries with higher electricity emission factors than natural gas showed increases in carbon emissions, with one UK study reporting an approximate 14 % rise in the future [50]. Similarly, Tamer et al. [75] observed an average increase from 7 to 11 kg CO2eq/m^2 in Turkey, due to lower carbon intensity for heating compared to cooling.

This study also employs dynamic electricity emission factors to analyze GHG emissions trends based on the AusLCI. This approach reveals a substantial reduction in GHG emissions (up to 70 % decreases) in most cities, with a noteworthy exception in Adelaide. The rise is due to the increase in GHG emissions coefficients from 0.085 (current) to 0.102 kg CO2eq/MJ (2050), as per AusLCI data, followed by a decrease to 0.080 kg CO2eq/MJ in 2080. This trend is unique and corroborated by projections from Australia's emissions projections 2023 for South Australia [77]. The reasons for changes in the electricity energy mix are beyond the scope of this research.

While previous studies employing static carbon intensity factors provide valuable insights [3,72,78], they cannot fully capture the evolving nature of building emissions, particularly given the dual impact

Table 5
Summary of findings from previous studies.

Building type	Time	Heating decrease	Cooling increase	Total (heating and cooling or HVAC)	Studied region	Reference
Residential	2090 vs baseline (1999–2015)	32–71 %	184–380 %	/	New Zealand	[4]
16 ASHRAE prototypes	Future (2041–2070 and 2056–2075) vs baseline (1959–1989 and 1998–2014)	18–33 %	15–126 %	/	Canada	[6]
Residential	2050, 2100 vs baseline (1990)	20–81 % (2050) 30–99 % (2080)	39–146 % (2050) 61–380 % (2080)	−26∼101 % (2050) −48–350 % (2080)	Australia	[17]
Office	2020, 2050, 2080 vs baseline	50–73 % (2080)	16–27 % (2080)	−0.6∼8.3 % (2080)	Australia	[18]
Residential	2020–2100	10–20 % (2100, SSP1-2.6) 30–50 % (2100, SSP5-8.5)	25–70 % (2100, SSP1-2.6) 150–570 % (2100, SSP5-8.5)	/	China	[63]
Office	2080 vs 2020	−51 %	+111 %	+7 %	Turkey	[75]
Residential	2010–2039 (NT), 2040–2069 (MT), and 2070–2099 (LT)	5.4–19.2 % (NT-MT) 3.6–19.7 % (MT-LT)	3–40 % (NT-MT) 2.9–36 % (MT-LT)	/	38 European cities	[22]
Residential	2050s VS baseline (1976–2005)	30.4–46.7 %	41.8–171.5 %	/	Italy	[74]

means data not available.

of climate change that affects both building energy demand and energy transition pathways across different scenarios. The evolution of energy systems and subsequent shifts in energy use patterns, intensities, and mixes will significantly impact building LCA [79]. For example, Xu et al. [80] projected electricity mix structures with different emission levels (450 and 550 ppm CO2eq scenario) for the period 2010–2100 in their LCA case study in China. Accurate assessment of climate change impacts on building emissions requires consideration of both dynamic energy demand and evolving energy mix patterns aligned with climate models and scenarios. This represents a limitation of the current study, as high-emission scenarios like SSP585 would likely have greater emission factors than low-emission scenarios such as SSP245. The use of uniform AusLCI data across different scenarios that would typically have distinct energy transitions may lead to an underestimation of scenario differences, suggesting that high-scenario building emissions could be substantially higher than projected.

Regional variations add another layer of uncertainty. For instance, Cirrincione et al. [81] assumed declining emission factors of 0.48, 0.20, and 0.18 kg CO2eq/kWh for 2020, 2050, and 2080 in Palermo. However, a study in Japan projected an increase in the electricity emission factor from 0.3 kg CO2eq/kWh in the 1990s to 0.5–0.6 kg CO2eq/kWh for future periods (2040 and 2090) [82], due to changes in nuclear share in electricity production. This underscores the importance of considering local energy policies and grid mix along with the climate models for future projections, which are often overlooked in broader studies. Furthermore, countries connected to global energy grids face additional complexities in predicting emissions, such as the influence of global socioeconomic development [83], policy decisions, and the variability of emission factors between peak and off-peak periods.

Finally, using static GHG emissions factors may underestimate the significance of applying ECM under the current conditions. Static scenario leads to the same carbon emissions savings for the same energy savings both now and in the future. However, future scenarios with greener and cleaner energy sources would lead to lower electricity GHG emissions coefficients. This highlights the importance of implementing ECMs immediately to curb energy use and carbon emissions, rather than postponing such measures.

4.3. Sensitivity analysis of ECM

ECMs are often selected for their immediate benefits that suit past and present climatic conditions. However, climate change alters the environmental factors for which these ECMs were designed, potentially making them obsolete or even counterproductive. This section presents a simple sensitivity analysis of various ECMs (Table 6) to evaluate their effectiveness under global warming. Two cities with divergent climatic characteristics and energy consumption patterns were selected for this analysis, i.e., Darwin and Hobart. Darwin, which represents a tropical climate zone with no heating requirements, is projected to face significant increases in cooling needs due to climate change. This makes it an ideal case study for evaluating ECMs in warm regions facing intensifying heat stress. Hobart, in contrast, is experiencing a shifting energy balance from heating-dominated to cooling-dominant. This location provides insights into ECM effectiveness in areas undergoing significant climate transitions. To understand the most severe scenario, SSP585_2080 was used to compare with the baseline.

4.3.1. Opaque envelope U-value

Building envelopes serve as the primary barrier against external environmental factors and climate change. In the sensitivity analysis, we simulated different thicknesses of insulation and calculated their U-value and associated EUI. As depicted in Fig. 3, there is a discernible correlation between the opaque envelope U-value (walls and roofs) and the overall EUI in office buildings. Typically, higher U-values are associated with increased operational energy demand. This aligns with the findings of Yu et al. [43], which reported a marginal rise in HVAC energy consumption corresponding to an uptick in U-value.

For Darwin, the sensitivity of EUI changes to the U-value is more pronounced than in Hobart, as indicated by the steeper slopes of the trend lines for both the baseline and future SSP585_2080. A notable discovery is that climate change seems to exacerbate the effects of U-value on the total EUI in Darwin. For instance, an increase in insulation from 0.02m (0.46 $W/(m^2·K)$) to 0.4m (0.09 $W/(m^2·K)$) for exterior wall results in reductions of 0.57 kWh/m^2 and 1.49 kWh/m^2 in total EUI for the baseline and SSP585_2080 scenarios, respectively. This observation aligns with findings in Iran [62], which advocated for the adoption of lower or lowest U-values in regions characterized by high cooling demands at present.

However, achieving lower U-values typically requires increased insulation thickness, which has implications for both embodied carbon and operational energy. Focusing on the operational stage and neglecting embodied impacts can lead to misguided decisions in the pursuit of low-carbon or energy-efficient buildings. The embodied impacts of building materials processing can contribute up to 50 % of whole life carbon emissions in high energy efficient buildings and more than 90 % in extreme cases [84]. To reveal the relationship between embodied and operational impacts, we quantified the embodied impacts of changing insulation based on dataset from the EPiC database in Australia (4.0 kg CO2e/kg for carbon and 57.5 MJ/kg for energy for Glasswool). Combining this data with the quantities of insulation obtained from Revit modeling for the office building, we calculated the embodied carbon and energy impacts of increased insulation. Furthermore, we converted MJ to kWh to facilitate comparison with operational energy savings.

Table 6
ECM considered and their input variables.

ECM	Unit	Range	Step	Coefficient (kWh/m^2)			
				Darwin baseline	Darwin SSP585	Hobart baseline	Hobart SSP585
Wall U-value	$W/(m^2·K)$	0.07–0.51[a]	/	1.59	4.03	2.80	1.24
Roof U-value	$W/(m^2·K)$	0.06–0.31[a]	/	4.46	10.13	9.89	3.41
Envelope solar absorptance	/	0.1–0.6	0.1	0.56	1.71	−1.13	−0.16
Window U-value	$W/(m^2·K)$	0.8–4.3	0.7	0.78	0.85	1.14	0.44
Window SHGC	/	0.2–0.7	0.1	27.18	31.67	−4.33	5.51
WWR		0.2–0.7	0.1	27.37	32.95	3.27	11.87
Infiltration rate	(m^3/s per m^2 facade)	0.0001–0.0006	0.0001	26028.86	42275.71	18558.86	7561.14
Extruded border shades	m	0–1.2	0.2	−2.65	−2.66	1.16	−0.33
Lighting load	W/m^2	1.5–16.5	3	5.06	5.13	3.74	4.19
Equipment load	W/m^2	3–23	4	5.61	5.83	3.69	4.32
Heating setpoint	°C	16–21	1	/	/	2.59	1.49
Cooling setpoint	°C	24–29	1	−2.81	−4.34	0.06	−0.10
Sensible heat recovery	/	0.2–0.7	0.1	−11.12	−16.70	−10.37	−3.20

[a] The U-values were calculated based on varying insulation thicknesses using glass wool insulation ($\lambda = 0.04$ $W/(m·K)$). The parametric analysis examined insulation thicknesses of 0.01–0.50 m for exterior wall and 0.05–0.60 m for roof, yielding the corresponding range of U-values.

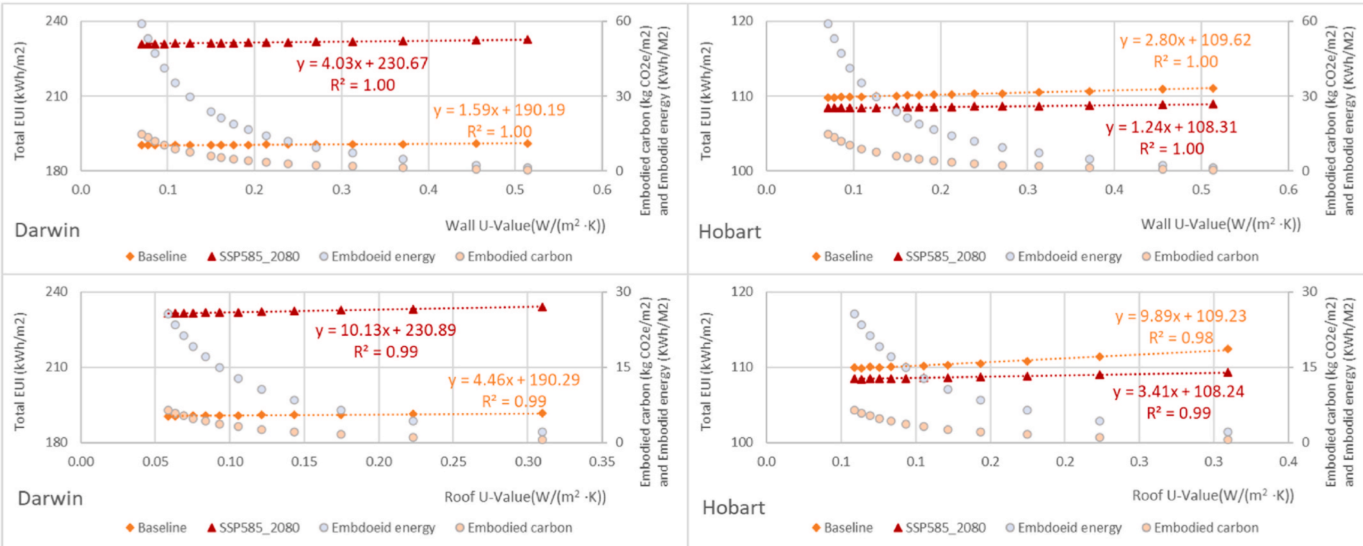


Fig. 3. Impacts of the opaque envelope U-value on the total EUI.

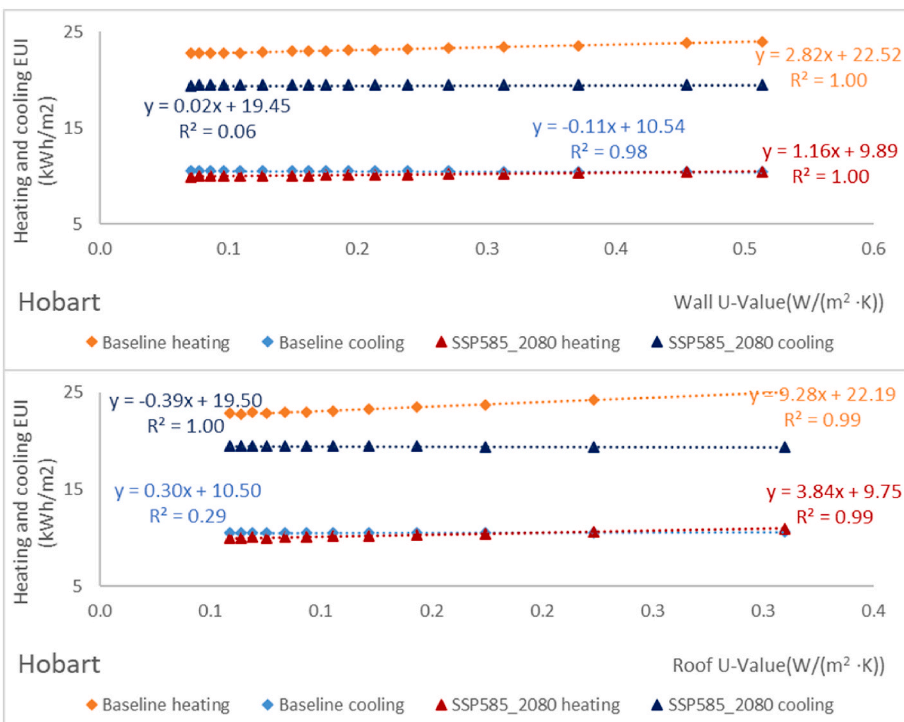


Fig. 4. Impact of the opaque envelope U-value on heating and cooling EUI in Hobart.

Adding 1 cm of insulation to the external wall contributes 0.30 kg $CO2e/m^2$ and 1.18 kWh/m^2, while the values for roofs are 0.11 kg $CO2e/m^2$ and 0.43 kWh/m^2. The total U-value has a discernible correlation with the total EUI but not with the embodied impacts (Fig. 3), as the U-value relationship with increasing insulation is not linear. These marginal effects highlight the importance of optimizing insulation thickness within a reasonable range to maximize energy efficiency while considering environmental impact. This emphasizes that future building design strategies under climate change must balance annual energy savings with life-cycle embodied carbon/energy.

In cooler climates like Hobart, climate change appears to mitigate the effect of insulation levels on total EUI. This is evident in Fig. 3, where the sensitivity coefficient for the future scenario is less than that of the baseline regarding the roof U-value. This phenomenon can be attributed to Hobart's climatic evolution, shifting from a heating-dominant to a cooling-dominant regime in the SSP585_2080 scenario. Within this scenario, an increase in wall U-value produces a marginal rise in heating EUI while having negligible impact on cooling EUI (Fig. 4). For the roof U-value under baseline period, heating sensitivity coefficients substantially exceed both cooling coefficients and future scenario responses.

4.3.2. Solar absorptance

Solar absorptivity measures the proportion of incident solar radiation absorbed by a surface. The darker the color of the material, the greater the solar absorption, which may be beneficial for heating but detrimental for cooling. Similar to the trend observed with opaque

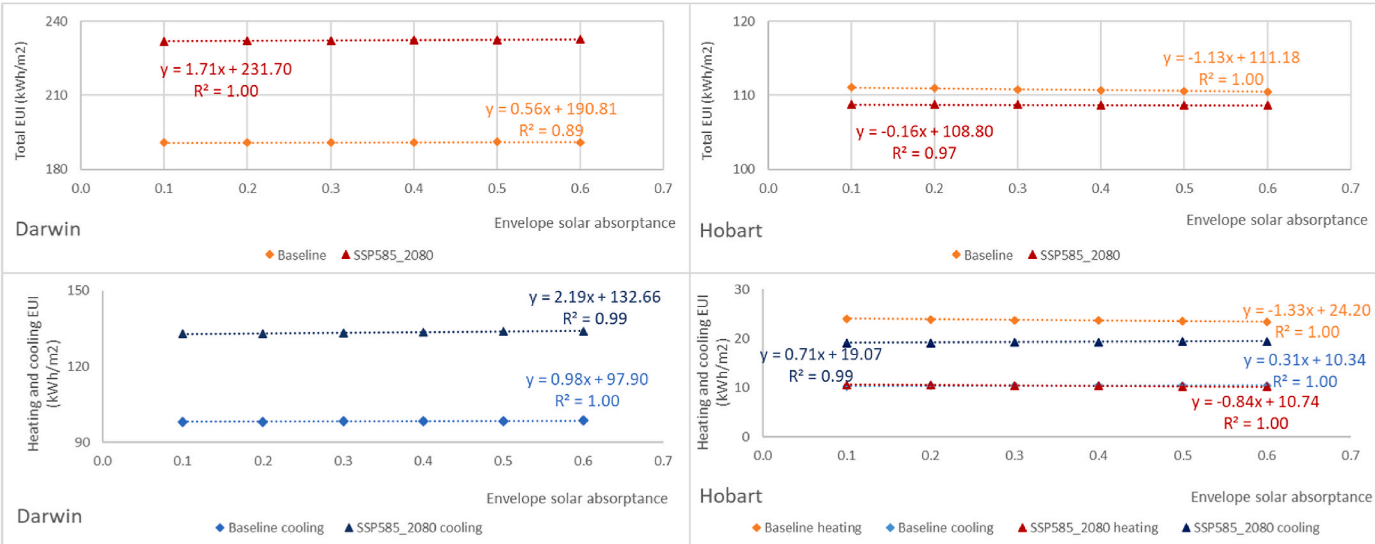


Fig. 5. Impact of solar absorptance on total, heating and cooling EUI.

envelope U-values, the influence of solar absorptance on total EUI is more obvious in Darwin than in Hobart (Fig. 5).

In Darwin, increasing envelope solar absorptance shows a positive correlation with total EUI, with climate change amplifying this effect. This amplification is directly reflected in cooling energy demands, where the sensitivity coefficient rises from 0.98 kWh/m^2 to 2.19 kWh/m^2 between baseline and future scenarios. Such change suggests that solar absorptance becomes increasingly critical in warmer climates under future scenarios, likely due to enhanced solar heat gain contributing to cooling loads.

Conversely, Hobart exhibits an inverse relationship, where increasing solar absorptance correlates with decreased total EUI. The sensitivity coefficient changes from −1.13 in the baseline to −0.16 kWh/m^2 in SSP585_2080, indicating a significant reduction in the parameter's influence. Heating demand shows decreasing sensitivity (from −1.33 to −0.84) while cooling sensitivity increases marginally (from 0.31 to 0.71). The opposing directions of these effects explain the reduced overall impact on total EUI, highlighting the changing balance between heating and cooling requirements. The beneficial solar heat gain in current conditions becomes less advantageous under warmer

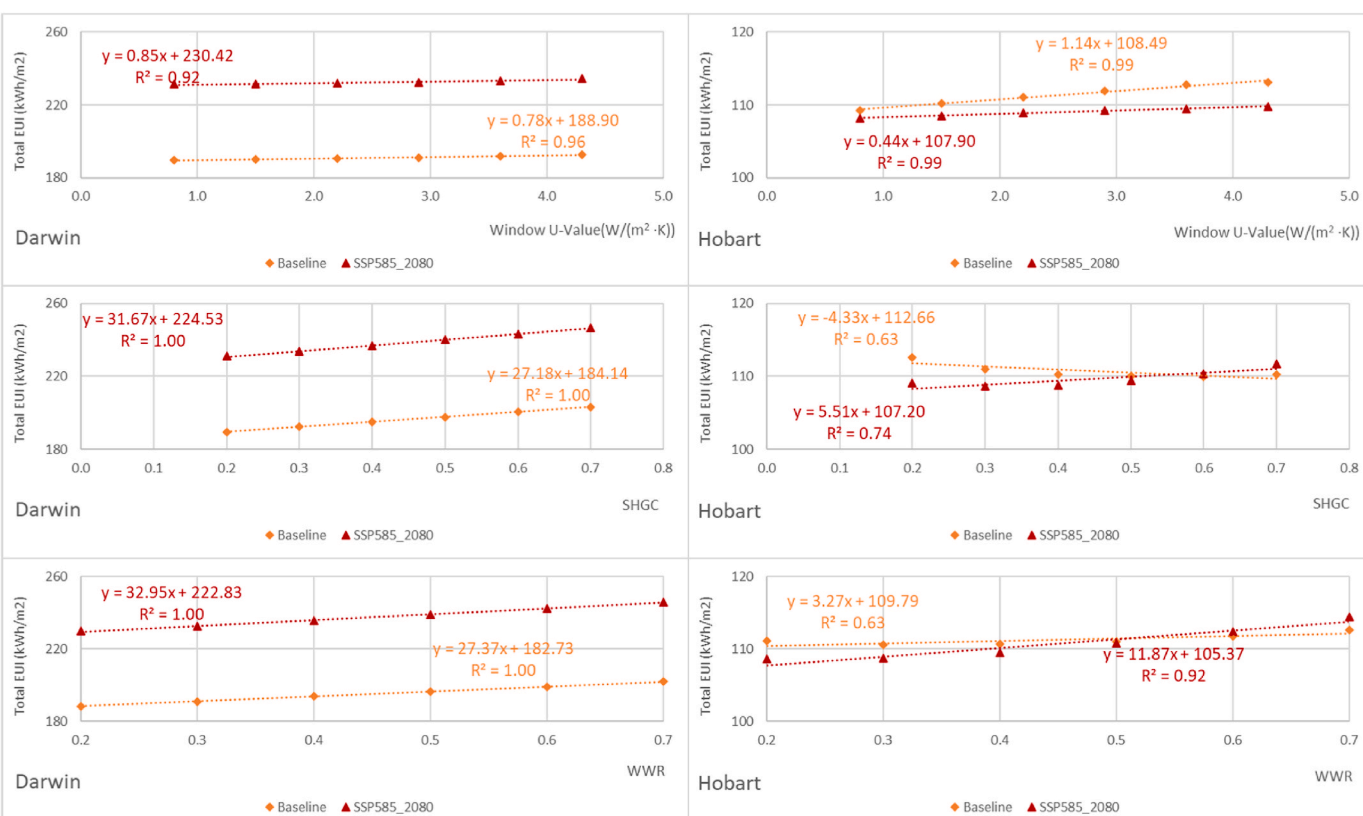


Fig. 6. Impact of window design on total EUI.

future scenarios, necessitating a more nuanced approach to building design.

4.3.3. Windows design

Windows play a crucial role in regulating heat transfer and solar heat gain through their thermal and optical properties. For U-value and SHGC, it should be noted that, in practice, U-value and SHGC will change and go hand in hand when the type of window changes. This study only tries to explore how this parameter will influence building energy under global warming and therefore focuses on value changes of the parameter.

Lower U-values, indicating improved window thermal performance, result in a slight decrease in total EUI (Fig. 6), with the impact being less pronounced than that of building opaque envelope U-values, based on the slope trends. However, SHGC exhibits a greater potential to influence building energy. In Darwin, a lower SHGC, which reduces solar heat gain through windows, leads to a notable decrease in total EUI. This effect will be amplified under the future SSP585_2080 scenario. Specifically, reducing the SHGC from 0.7 to 0.2 would lead to a decrease of 13.62 kWh/m^2 and 15.77 kWh/m^2 in the baseline and SSP585_2080 scenarios, respectively.

An interesting finding is that in the cooler climate of Hobart, increasing the window SHGC decreases the total energy consumption under the baseline scenario but increases it under the future climate scenario. Specifically, a 0.5 increase from 0.2 to 0.7 in SHGC would lead to a 2.32 kWh/m^2 (2.10 %) decrease and a 2.69 kWh/m^2 (2.41 %) increase in total EUI for the baseline and SSP585_2080 scenarios, respectively. This means that while solar heat gain is beneficial for energy efficiency under current conditions, solar control will become more essential for energy efficiency in the SSP585_2080 scenario. This finding aligns with previous research by Bamdad [15], who demonstrated similar shifts in cool roofs in Canberra and Melbourne. ECMs that are beneficial in the current situation may not be effective in the future, and vice versa. These context-dependent shift patterns highlight that ECMs are inherently climate-sensitive, with their effectiveness varying based on environmental conditions, building usage patterns, and technological advancements. This understanding underscores the need to develop adaptive and forward-looking strategies to ensure energy efficiency across evolving climatic scenarios while maintaining thermal performance resilience.

Window area, represented by the WWR, significantly influences building energy performance through both solar heat gains and heat transfer. Increasing WWR leads to higher total EUI in both Darwin and Hobart, with the impact becoming more pronounced under future climate scenarios. In Darwin, the sensitivity to WWR changes is considerably higher in the SSP585_2080 scenario (slope = 32.95) compared to the baseline (slope = 27.37). Specifically, increasing WWR from 0.2 to 0.7 results in an increase of 13.70 and 16.31 kWh/m^2 under baseline and SSP585_2080, respectively. Hobart demonstrates a more moderate response to WWR variations with lower sensitivity coefficients: 3.27 kWh/m^2 per unit WWR change in the baseline scenario and 11.87 kWh/m^2 in SSP585_2080.

The analysis also suggests that current WWR design decisions should consider future climate scenarios, as the energy implications of window area choices become more significant under warming conditions and are typically costly and difficult to modify post-construction. While decreasing WWR improves energy efficiency, it presents important trade-offs that must be considered. Reduced window areas may negatively impact daylighting quality and occupant well-being. Furthermore, the embodied carbon implications add another layer of complexity, as decreased WWR typically requires more envelope materials, potentially increasing embodied impact. These competing factors necessitate a careful balance in future design optimization.

To better understand these trends, Fig. 7 illustrates how window properties influence heating and cooling EUI. The results demonstrate that increasing window SHGC amplifies cooling energy sensitivity under future periods compared to the baseline, with Darwin showing notably higher sensitivity coefficient (21.24–24.38). A similar trend emerges for

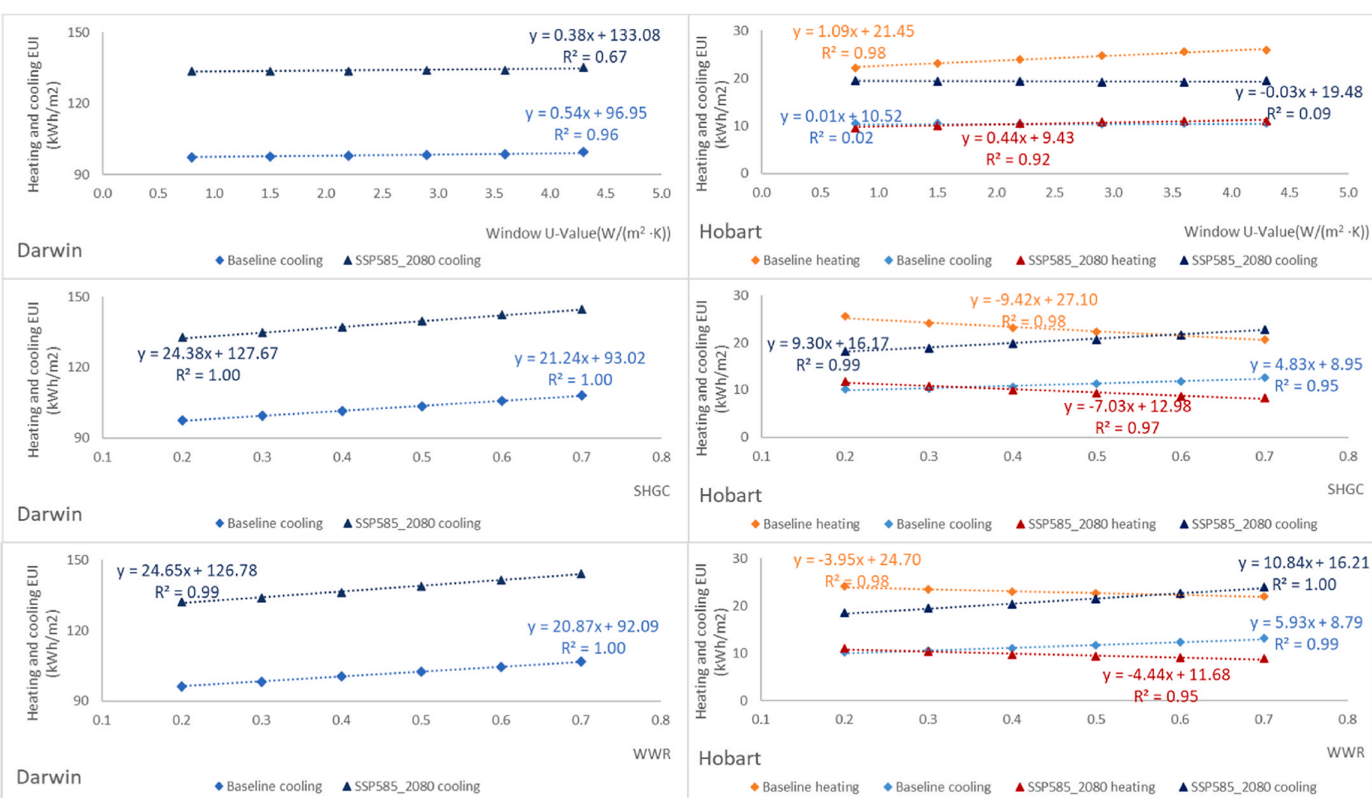


Fig. 7. Impact of window U-value, SHGC and WWR on heating and cooling EUI.

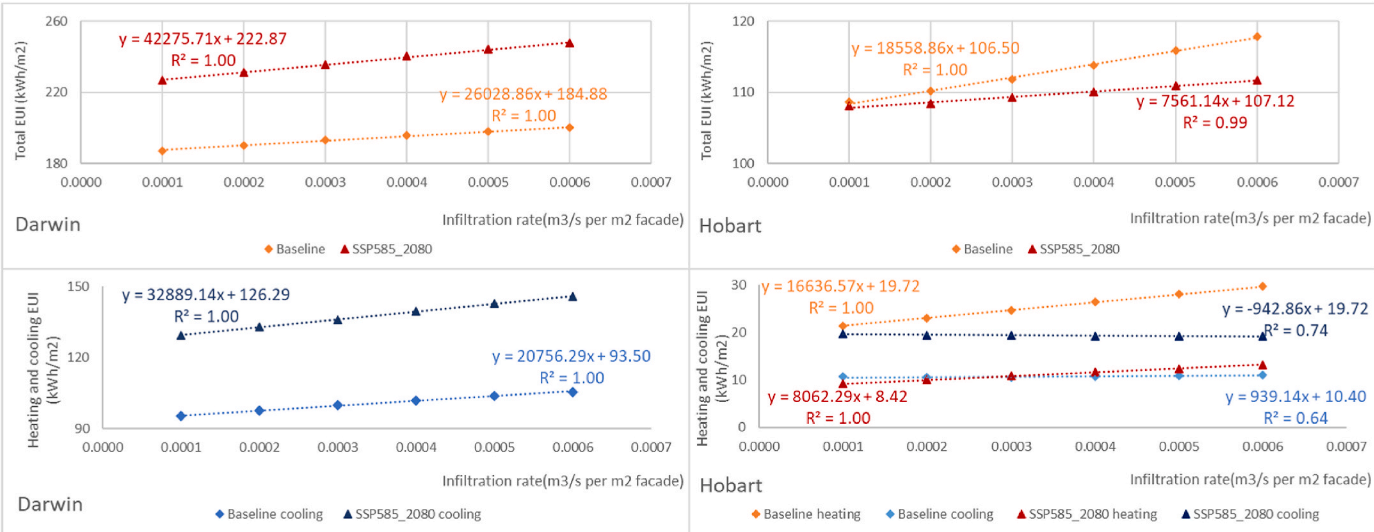


Fig. 8. Impact of infiltration rate on total, heating and cooling EUI.

WWR, which exhibit amplified effects on cooling loads in future scenarios, particularly evident in Darwin where the sensitivity coefficient increases from 20.87 to 24.65. In contrast, Hobart displays more complex behavior, where climate change reduces the impact on heating EUI for SHGC variation in future SSP585_2080 (−7.03) compared to baseline (−9.42), but intensifies the effect for WWR changes (−3.95 in baseline to −4.44 in future scenario). Compared to the other two window parameters, window U-value has a minimal impact on both heating and cooling EUI across baseline and future periods in both cities.

4.3.4. *Infiltration rate*

The infiltration rate is used to quantify the uncontrolled air exchange between indoor and outdoor environments. In Darwin, an increase in infiltration rates results in a substantial rise in total EUI for both the baseline and SSP585_2080 scenarios (Fig. 8). This trend can be attributed to the additional cooling load imposed by the influx of hot outdoor air, which needs to be cooled to maintain thermal comfort. Notably, the impact of infiltration will be exacerbated by the continued warming of the climate.

In contrast, the total EUI is more sensitive to infiltration in Hobart under the baseline scenario. In the SSP585_2080 scenario, the heating EUI becomes less sensitive to infiltration. The observation indicates that a higher infiltration rate may be slightly beneficial for cooling in Hobart, as it may allow the influx of cooler outdoor air during the night or early morning hours, potentially reducing the need for mechanical cooling. Conversely, in Darwin, a higher infiltration rate is disadvantageous due to the influx of hot outdoor air, which increases the cooling load. This emphasizes the need for further isolation from the outdoor environment in hot areas in the future.

4.3.5. *Shading*

Effective shading can reduce solar heat gain and the associated cooling load required in hot regions. In Darwin, increasing the depth of shades leads to a decrease in total EUI for both the baseline and SSP585_2080 scenarios (Fig. 9). Specifically, increasing the depth of shades from 0.2 to 0.4 m would result in a reduction of 0.73 and 0.64 kWh/m^2 in total EUI for the baseline and SSP585_2080 scenarios, respectively. In contrast, the impact of shading on total EUI exhibits a contrasting trend in Hobart, similar to the effect observed with window SHGC. Under the SSP585_2080 scenario, solar control strategies become favorable though to a lesser extent. While deeper louvers effectively reduce cooling loads by limiting solar heat gain, they also lead to a rise in heating EUI due to the reduced solar heat gains during the heating season. This underestimates the significance of occupant behavior in enhancing shading performance. Occupant-controlled shading offers the advantage of reducing overheating while simultaneously maximizing solar radiation for heating, as opposed to fixed shading [85].

4.3.6. *Internal heat gains (IHG)*

Unlike residential buildings, maintaining thermal comfort in office buildings is highly influenced by artificial lighting, equipment, appliances, and occupant density, which contribute to IHG (Fig. 10).

The results highlight that increasing IHG significantly impacts lighting and equipment EUI while simultaneously increasing cooling energy demands in both cities (Fig. 11). Notably, the impact of IHG on total and cooling EUI is slightly more pronounced in future climate conditions for both cities. For instance, reducing the lighting load from 4.5 to 1.5 W/m^2 would lead to a decrease in cooling EUI of 2.28 and 1.96 kWh/m^2 for Darwin's baseline and future climate scenarios, respectively. These observations emphasize the importance of reducing

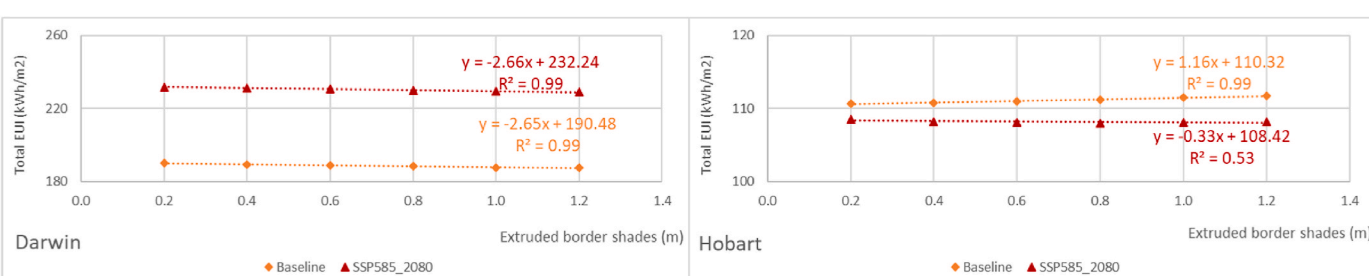


Fig. 9. Impact of shading on total EUI.

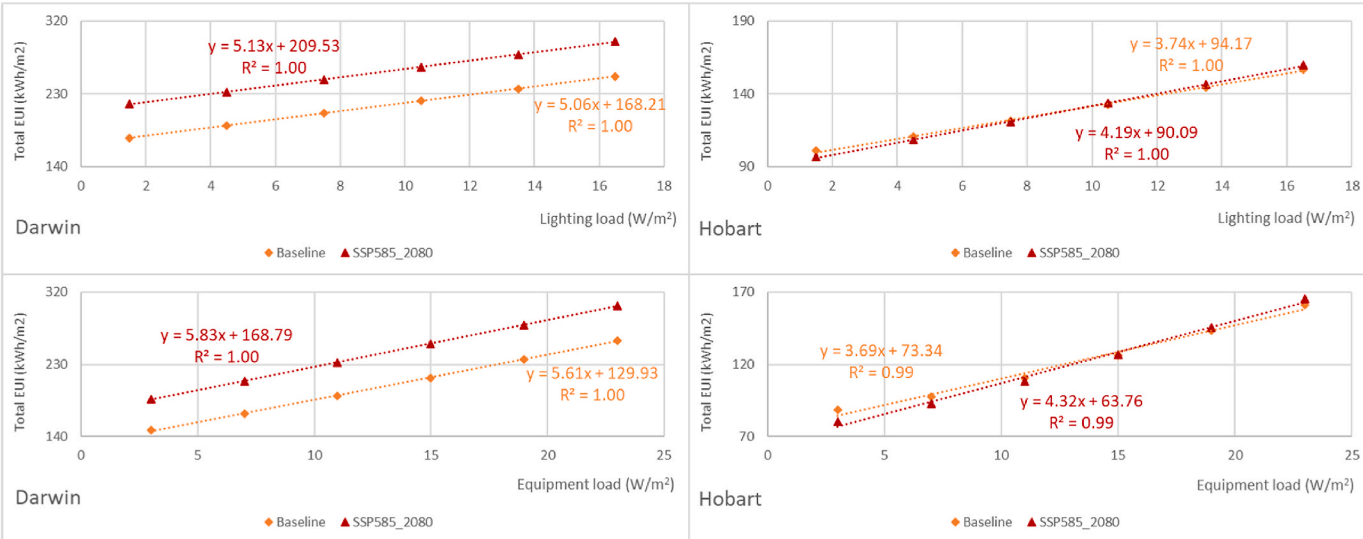


Fig. 10. Impact of internal heat gains on total EUI.

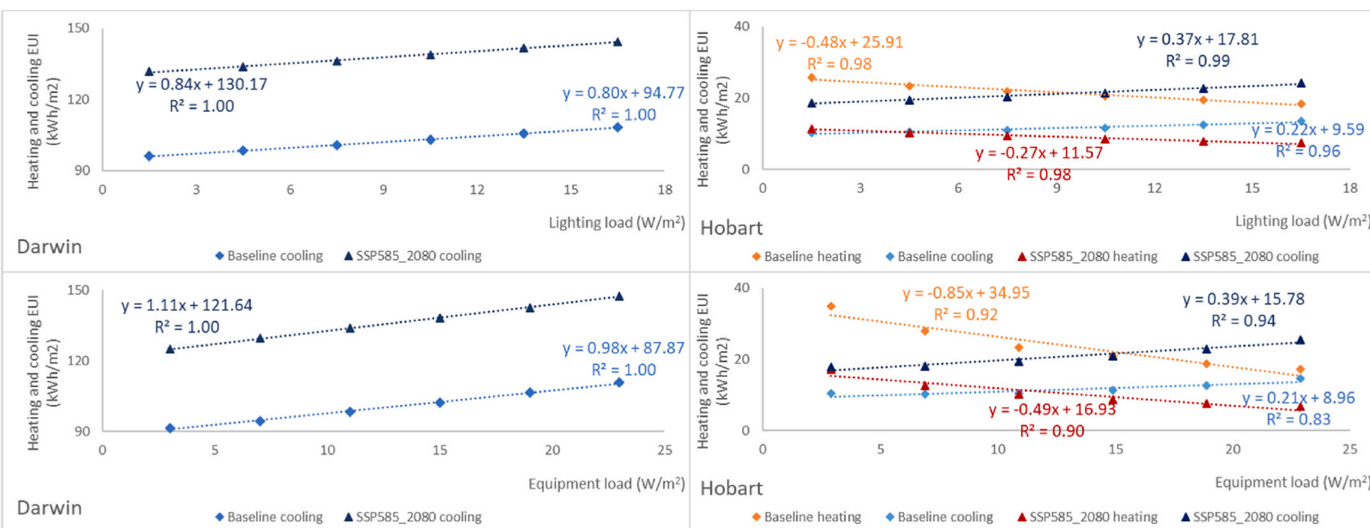


Fig. 11. Impact of internal heat gains on heating and cooling EUI.

IHG in building design. Berger et al. [86] reported that the impact of IHG energy efficiency on net cooling demand was more significant than the impact of global warming. Similar findings were observed by Bamdad et al. [13], who showed that different internal load scenarios (low, base, and high) had a more substantial impact than optimization and global warming for Brisbane office buildings.

In Hobart, the sensitivity analysis reported a decreasing trend in heating EUI with increasing IHG, an effect that slightly diminishes with climate change, as indicated by the flatter slope. A reduction in equipment loads from 11 to 7 W/m^2 would result in an increase in heating EUI of 4.47 and 2.35 kWh/m^2 and a decrease in cooling EUI of 0.20 and 1.21 kWh/m^2 under the current and future climates, respectively. A similar trend is observed for lighting loads. However, heating buildings using IHG is highly inefficient and should not be considered a rebuttal for improving lighting and IT equipment efficiency.

Curbing IHG not only directly decreases the electricity consumed by lighting and equipment but also indirectly reduces cooling loads exacerbated by climate change. This is particularly crucial in hot climate offices where heating is not required, as reinforced by Wan et al. [49, 87]. In Ref. [88], modifying IHG from a high to medium scenario could result in a decrease in GHG emissions from 230 % to 70 % and from 480 % to 140 % by 2050 in rural and urban areas, respectively.

While future technological advances may improve lighting and equipment energy efficiency, an increase in energy-intensive devices is also plausible. As explored in two divergent scenarios by Daly et al. [18], there could be either a low energy intensity of internal loads driven by planning for carbon neutrality or a high energy intensity of IT devices driven by maximizing productivity. Particularly, the unstoppable growth of artificial intelligence may lead to an inevitable increase in equipment loads in office and data center buildings, necessitating strategies to curb energy consumption in high internal heat gain situations. Without such strategies, HVAC systems could be severely strained during extreme heat waves, risking power shortages when operating at full capacity. Calculating carbon emissions in such scenarios can be complex. Both average and marginal emission factors need to be considered, as emissions during peak load operations may significantly exceed usual levels.

4.3.7. Occupant behavior: modifying setpoints

Occupant behavior can have a significant influence on the indoor

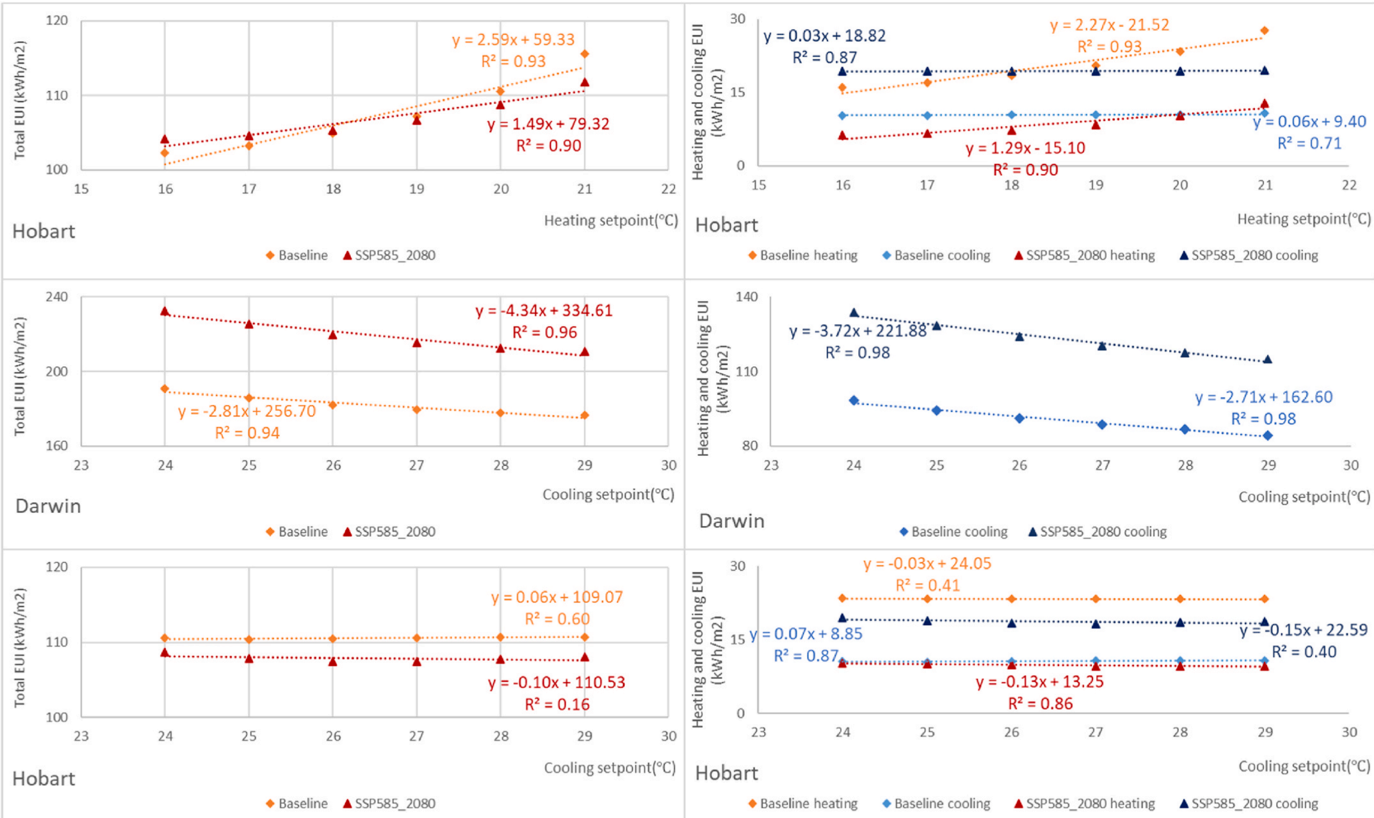


Fig. 12. Impact of modifying heating and cooling setpoints on total, heating and cooling EUI.

environment, so methods for modifying setpoints as ECMs were investigated. Changing the setpoints and their associated heating, cooling and total EUIs are shown in Fig. 12.

In Darwin, the slope of the linear line is steeper under the SSP585_2080 scenario compared to the baseline, indicating a more pronounced impact of cooling setpoint changes on total and cooling EUI in future weather. The impact is more significant in Darwin than in Hobart. Specifically, for Darwin, an elevation of the cooling setpoint by 1 °C is associated with a decrement in the total EUI by 2.81 kWh/m^2 for the baseline scenario and 4.34 kWh/m^2 for the SSP585_2080 scenario. These findings are consistent with the Canadian study [76], which indicated that raising the cooling setpoint by 1 °C (24–25 °C) would lead to energy savings of 0.9 %, 1.6 %, and 1.4 % in Quebec, Toronto, and Vancouver, respectively. For the future period 2056–2075, these values are projected to increase to 1.5 %, 2.0 %, and 2.1 %, respectively.

In contrast, the cooling setpoint in Hobart has a negligible effect on total and cooling EUI, as shown by the relatively flat linear regression lines. As there is no heating requirement in Darwin's hot climate, changing heating setpoints is not applicable in this region. In Hobart, however, the impact of modifying heating setpoints is diminished by climate change, as indicated by the steeper slopes in the baseline.

This finding suggests that modifying cooling setpoints may be a more beneficial zero-cost measure in warmer climates like Darwin. Moreover, this behavior can be justified by considering adaptive thermal models [17], where occupants adapt to rising temperatures due to climate change. For instance, a 0.6 °C rise in the upper limit of thermal comfort has been observed [52].

4.3.8. HVAC system efficiency

The technological evolution of HVAC systems, particularly regarding heat recovery capabilities and operational efficiency metrics, represents an essential factor in climate change adaptation strategies for buildings. This study investigates the effectiveness of sensible heat recovery systems to explore the broader context of HVAC technology advancement.

Analysis of sensible heat recovery effectiveness demonstrates distinct climate-dependent patterns (Fig. 13). In Darwin, the sensitivity coefficient increases substantially from −11.12 in the baseline scenario to −16.70 under SSP585_2080, representing a 50 % enhancement in energy reduction potential. This amplification suggests that heat recovery systems effectiveness increases with climate warming in tropical regions

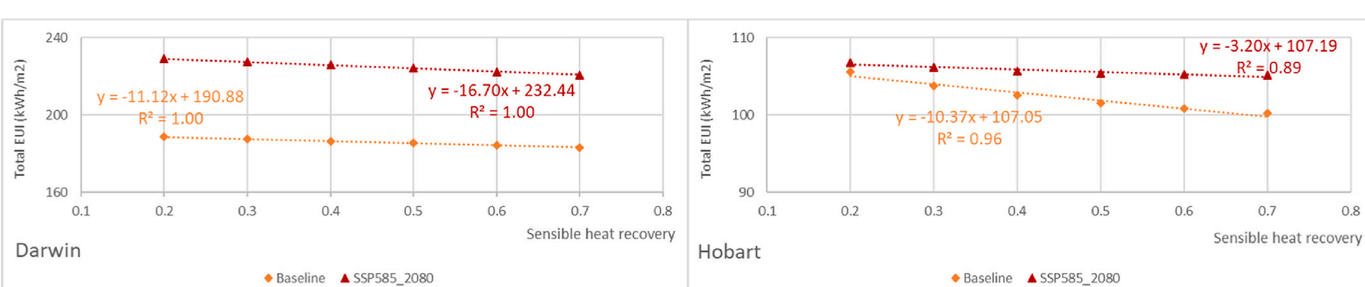


Fig. 13. Impact of the sensible heat recovery on total EUI.

like Darwin. Conversely, Hobart exhibits an inverse trend. The baseline scenario demonstrates a sensitivity coefficient of −10.37 (R^2 = 0.96), which diminishes to −3.2 (R^2 = 0.89) under SSP585_2080. This substantial reduction in system effectiveness highlights the challenges posed by the region's ongoing transition, emphasizing the need for adaptive technological solutions that can accommodate shifting climate patterns.

This analysis of sensible heat recovery demonstrates how technological improvements in HVAC systems can help mitigate the impacts of climate change on building energy consumption. Technological advancement trajectories suggest continued improvements in system efficiency metrics, such as coefficient of performance (COP) and energy efficiency ratio (EER) of heating and cooling systems [89]. Climate change studies demonstrate promising results of improving HVAC system efficiency. For instance, improving the COP of the chiller from 3.0 to 6.0 resulted in a significant energy saving of about 16 kWh/m^2 in total primary energy [47]. Barea et al. [90] also explored technological advancements in chiller COP and assumed COP efficiency to increase from 2.3 in 2020 to 3.5 in 2075 and 4.4 in 2099, reporting that cooling would drop to even lower levels than current.

However, several complex factors challenge their real-world effectiveness. First, system degradation over time emerges as a significant concern, with Waddicor et al. [47] indicating that the lower efficiency of the chiller was more influential than the climate change impact on cooling load. Second, multiple studies [33,40,91] have reported an inverse relationship between ambient temperature and cooling system EER. This relationship becomes particularly concerning when considering the growing frequency of extreme weather events by climate change and intensifying UHI effects [92]. Such conditions could risk exceeding HVAC system capacities, potentially leading to compromised efficiency, and even system failures during peak demand periods.

4.3.9. Summary

The comprehensive sensitivity analysis conducted in this investigation reveals significant heterogeneity in ECM effectiveness across diverse climatic contexts. In hot climates, exemplified by Darwin, the efficiency of solar control measures reveals an increase under projected climate change scenarios. Of particular significance, measures that enhance building envelope isolation from the external environment, such as optimized U-values and reduced infiltration rates, exhibit heightened importance in future tropical conditions, by minimizing heat gains and associated cooling energy loads.

In regions undergoing climate transition, as illustrated by Hobart, the optimization of ECM implementation presents increased complexity due to the dynamic interplay between heating and cooling requirements. Notable findings indicate that contemporary solar control strategies, while potentially counterproductive in current conditions, may achieve enhanced effectiveness under future scenarios. Furthermore, the research identifies the significance of IHG reduction as a universal strategy for moderating building energy consumption, with particular emphasis on its amplified impact in warm climate zones.

This investigation underscores the importance of adopting an integrated life cycle perspective in ECM selection and implementation, given the temporal variability in measure effectiveness under evolving climatic conditions. Moreover, the analysis reveals that focusing solely on operational energy reductions may lead to suboptimal outcomes, as embodied carbon can constitute a significant proportion of building life cycle emissions. For instance, increasing insulation thickness, while beneficial for operational energy reduction, demonstrates diminishing returns when embodied impacts are considered. This complex interplay between embodied and operational impacts necessitates careful optimization and represents a crucial consideration for future research. The findings demonstrate the imperative for regional specificity in ECM prioritization, with warm climate zones necessitating robust solar control and thermal isolation strategies, while transitioning regions require the implementation of adaptable approaches to address shifting thermal demands. These insights contribute to the advancement of climate-resilient and future-oriented building design.

5. Conclusions

This study provides significant insights into the impact of climate change on the thermal performance and ECM effectiveness of office buildings across Australia. A typical 10-storey building was modeled in Rhino, and simulations were conducted in Grasshopper with Ladybug tools. Key findings include:

Temperatures are anticipated to rise significantly by 2050 and 2080, with some regions experiencing monthly temperature increases of up to 5 °C by 2080. Extreme temperatures will become more prominent, with highs potentially exceeding 40 °C. Cooling demands are projected to increase by up to 38 % in warmer areas under the SSP585 scenario for 2080, while heating demands could decrease by 48–81 %. In addition, this study uniquely quantified the potential transformation of heating-dominated regions (e.g., Hobart) into cooling-dominant environments due to climate change. This research highlighted static coefficients suggest up to a 20 % increase in emissions for most cities, except for declines in colder regions. However, dynamic coefficients indicate potential 70 % reductions, emphasizing the importance of both building-level ECMs and grid decarbonization.

Furthermore, this study revealed novel insights into ECM effectiveness under climate change. In consistently warm areas like Darwin, solar control measures impact is amplified along with climate change. In transitioning climates like Hobart, previously detrimental strategies (e.g., shading) may become beneficial as cooling needs increase. Reducing IHG is essential for lowering total EUI, particularly in future climate conditions where they will become more pronounced in hot areas. Energy-efficient lighting and IT devices not only decrease electricity consumption but also reduce cooling demands. While this may slightly increase heating needs, this is not a rebuttal as heating via IHG is extremely inefficient. Encouraging energy-efficient occupant behaviors, such as adjusting setpoints, can enhance building performance and reduce overall energy use, especially for Darwin.

The study provides several recommendations for building design, energy management, and policy development.

1. **Localized and flexible ECM strategies**: The varying effectiveness of ECMs across different climate zones and time periods highlights the need for context-specific interventions rather than one-size-fits-all solutions, especially in the present. This also emphasizes the importance of flexible and adaptive ECMs that can adjust to climate change, potentially shifting from solar favoring to solar control strategies and from passive to active cooling.
2. **Life cycle perspective**: This research underscores the need for a life cycle approach in implementing ECMs, as buildings often operate for more than 50 years. ECMs that are beneficial under current conditions may become detrimental in the future, and vice versa. Furthermore, this perspective highlights the significance of considering both operational and embodied energy from building materials, as increasing insulation may decrease operational energy but increase embodied energy.
3. **Policy implications**: The study emphasizes the need for climate-adaptive building design strategies across diverse climate zones. It suggests that building standards may require dynamic updates to ensure future-proof ECMs, especially for regions experiencing climate transitions.

This research contributes significantly to the Australian context by enhancing knowledge of future office building thermal performance across diverse climate zones. Internationally, it provides a methodological framework for quantifying the implications of climate change on thermal performance and ECM effectiveness, which can be applied to other regions and extended to other ECMs.

However, this study has several limitations. It focuses on a limited set of basic ECMs, whereas future research could explore a broader range of innovative materials and technologies, such as dynamic façades and renewable energy integration. Furthermore, the use of a uniform emissions coefficient for electricity across different climate change scenarios may underestimate variations between high- and low-emission pathways, as future energy transitions could differ significantly depending on climate scenarios and models. Another critical limitation lies in the consideration of embodied impacts. Future research should prioritize whole life cycle analyses that incorporate trade-offs between embodied and operational impacts under climate change. Moreover, expanding the scope to neighborhood, city, and national levels could provide valuable insights into broader district energy performance. Finally, this study does not account for economic factors and broader climate change parameters (e.g., humidity, solar radiation, rainfall and wind patterns), which also influence ECM implementation decisions.

CRediT authorship contribution statement

Zhuocheng Duan: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Conceptualization. **Hossein Omrany:** Writing – review & editing, Supervision. **Jian Zuo:** Writing – review & editing, Supervision.

Declaration of competing interest

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

Appendix. Table A1

Summary of recent research (2021-present) on the impact of climate change on building thermal performance.

Focus	Region	Scope	Building type	Future scenarios	Methods/Tools for generating future weather	Ref
Building	Portugal/Greece/Spain/Italy/France/Denmark/Finland	Heating and cooling electricity demand; Generating future weather files	Office	SSP1-2.6/SSP2-4.5/SSP3-7.0/SSP5-8.5	Morphing	[28]
Building	China	Heating and cooling	Residential	SSP1-2.6/SSP2-4.5/SSP3-7.0/SSP5-8.5	/	[63]
Building	Spain/UK	Heating and cooling; UHI and CC; TC	Residential	RCP8.5	Meteonorm	[38]
Building	Iran	HVAC electricity; Building codes; Different floors	Residential	SSP2-4.5/SSP5-8.5	Future Weather Generator	[61]
Building ECM	Cross country studies (13 Koppen climate zones)	Cooling energy saving; ECM (PCM)	Residential	RCP8.5	Hybrid downscaling (dynamical and statistical)	[34]
Building	Qatar	Heating and cooling; LCA	8 USDOE	RCP4.5	/	[93]
Building	Belgium	Static and dynamic LCA; Energy mix	Office	RCP8.5	Dynamical downscaling	[94]
Building	China	heating and cooling; Uncertainties (building characteristics and use patterns)	Residential	SSP1-2.6/SSP2-4.5/SSP3-7.0/SSP5-8.5	Morphing	[95]
Building	Turkey	Heating and cooling; GHG emissions and costs; PV energy generation	Office	A2	CCWorldWeatherGen	[75]
Building	US	LCGHGE (dynamic); occupant comfort	Office	RCP4.5/RCP8.5	WeatherShift	[96]
Building	Italy/Denmark	Heating and cooling	Office	RCP2.6/RCP4.5/RCP6.0/RCP8.5	Morphing	[36]
Building	Australia	(Peak) heating and cooling; Eight extreme weather scenarios	Office	A2/RCP8.5	CCWorldWeatherGen/CSIRO	[16]
Building	Sweden	Heating and cooling; TC; Extreme weather events and microclimate	Residential	RCP2.6/RCP4.5/RCP8.5	Dynamical downscaling	[68]
Building	Sweden/Italy/Austria/Spain/France/Germany/Portugal	Heating and cooling; Cost-optimal efficiency measures; Baseline vs NZEB	Residential	RCP8.5	Morphing	[30]
Building	Australia	HVAC energy use	Hospital	RCP8.5	CSIRO	[97]
Building	China	Heating and cooling; overheating	Residential/Office	A2	CCWorldWeatherGen	[98]
Building	Italy	Heating and cooling; Resilience of energy balance	Residential	RCP4.5/RCP8.5	WeatherShift	[99]
Building	Belgium	Time-integrated discomfort; HVAC primary energy; GHG emissions	Residential	SSP2-4.5/SSP3-7.0/SSP5-8.5	Dynamical downscaling	[72]
Building	US	Heating and cooling; GHG emissions; PV	Office	RCP8.5	Stochastic	[100]
Building	UK	HDD and heating energy; heating GHG emissions	Educational	A1FI/A1B	Dynamical and statistical	[101]
Building	Greece	Heating and cooling; microclimate (UHI)	Residential	A1B/RCP4.5	Meteonorm and dynamical downscaling	[102]
Building	Australia	Heating and cooling	Residential	RCP2.6/RCP4.5/RCP8.5	Morphing	[71]
Building	UK	Heating and cooling (primary) energy; GHG emissions	Supermarket	A1FI/A1B/B1	UKCP09	[103]
Building	Poland	Heating and cooling	16 USDOE	A2	CCWorldWeatherGen	[104]
Building	Brazil	Life cycle energy; LCGHGE; LCC; discomfort degree-hours	Residential	A2	CCWorldWeatherGen	[105]

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Focus	Region	Scope	Building type	Future scenarios	Methods/Tools for generating future weather	Ref
Building	US	Cooling; XAI model to predict cooling	Residential/Office	SSP1-2.6/SSP2-4.5/SSP3-7.0/SSP5-8.5	Statistical downscaling (z-factor scaling)	[60]
Building	China	LCGHGE	Residential	A2	CCWorldWeatherGen	[78]
Building	New Zealand	Heating and cooling	Residential	RCP4.5/RCP8.5	Meteonorm	[4]
Building	Italy	Heating and cooling	Residential	A2	CCWorldWeatherGen	[91]
Building ECM	Italy	Heating and cooling; Occupant behavior; LCA benchmark and LCA climate change	Residential	A2	CCWorldWeatherGen	[106]
Building ECM	Canada	Heating, cooling and total; TC; ECM (modifying setpoints)	Office	RCP8.5	WeatherShift	[76]
Building ECM	Sweden/Russia/Germany/Slovenia/Italy/Spain/Greece/Portugal	Heating and cooling; ECM (U-value, SHGC, NV, window-to-floor ratio, window distribution, shape factor, heat storage, surface absorptivity)	Residential	A2	CCWorldWeatherGen	[107]
Building ECM	Turkey	Heating and cooling; UHI; GHG emissions; TC; ECM (u-value, shading, green roofs, window properties)	Educational	RCP8.5	WeatherShift	[108]
Building ECM	Portugal/Spain	Heating and cooling; ECM (Heat pump, personal comfort systems and natural ventilation)	Office	/	/	[33]
Building ECM	Australia	Heating and cooling; Cool roofs	Residential	RCP4.5/RCP8.5	Morphing	[15]
Building ECM	Iran	Heating and cooling; ECM (random U values)	Residential	SSP5-8.5	Future Weather Generator	[62]
Building ECM	Montenegro	Heating and cooling; ECM	Residential	RCP4.5/RCP8.5	WeatherShift	[109]
Building ECM	India	Heating and cooling; TC; ECM (orientation, U-value, airtightness and WWR)	Residential	A2	CCWorldWeatherGen	[110]
Building ECM	Belgium	Heating and cooling (peak/primary) energy; TC; GHG emissions; ECM (HVAC)	Office	SSP2-4.5/SSP3-7.0/SSP5-8.5	Dynamical downscaling	[111]
Building ECM	Brazil	Heating and cooling, and equivalent index of performance; 13 design variables; TC	Residential	A2	CCWorldWeatherGen (Morphing)	[112]
Building ECM	Australia	Cooling and total energy; ECM (NV and ceiling fans)	Office	A1FI/B2	Morphing	[57]
Building ECM	Iran	Heating and cooling energy demand; GHG emissions; ECM (green envelope)	Residential	RCP2.6	Meteonorm	[113]
Building ECM	Argentina	Heating, cooling and UDI; ECM (NV, night ventilation, COP)	National public administration	RCP8.5	Morphing	[90]
Building ECM	Morocco	Cooling; free-running and air-conditioned; ECM (PCM)	Office	RCP4.5	Meteonorm	[114]
Building ECM	Russia/Slovenia/Italy/Portugal/Greece	Heating and cooling demand; ECM (U-value, SHGC, shape factor, NV, window-to-floor ratio, heat storage, solar absorptance)	Residential	A2	CCWorldWeatherGen	[35]
Building ECM	China	Life cycle energy; ECM (WWR, U-value, SHGC)	Residential	RCP2.6/RCP4.5/RCP6.0/RCP8.5	Morphing	[115]
Building ECM	Poland	Heating and cooling energy demand; TC; mechanical/passive cooling; standard/passive insulation	Residential	A2	CCWorldWeatherGen	[116]
Building ECM	Italy	Heating and cooling energy demand; TC; Existing and refurbished	Residential	RCP4.5/RCP8.5	WeatherShift	[70]
Building ECM	Chile	Heating energy demand; ECM (optimal U value); GHG emissions	Residential	RCP2.6/RCP8.5	Morphing	[117]
Building ECM	India/Pakistan/Vietnam/Nepal/China	Heating and cooling; ECM(PCM)	Office	RCP8.5	Whitebox (dynamical and statistical)	[118]
Building ECM	Cyprus	HDH and CDH; TC; 32 retrofit scenarios	Educational	A1B	Meteonorm	[119]
Building ECM	Italy	Heating; TC; Retrofit ECM	Residential	RCP8.5	Dynamical downscaling	[120]
Building ECM	Italy	Heating and cooling; PV production; Three weather file; Refurbishment	Residential	RCP4.5/RCP8.5	WeatherShift	[121]
Neighborhood scale	Switzerland	Heating and cooling; two neighborhoods; ECM	Residential	SSP1-2.6/SSP2-4.5/SSP3-7.0/SSP5-8.5	Future Weather Generator	[41]
Neighborhood scale	UK	Total energy demand; urban built forms and urban geometry; EV and PV	Residential	A2	Meteonorm	[122]
Building stock	US	Electrical and natural gas usage of commercial building	16 USDOE prototype	RCP2.6/RCP4.5/RCP8.5	Downscaling	[123]
Building stock	Finland	Heating demand Four renovation scenarios	Residential/non-Residential	RCP2.6/RCP4.5/RCP8.5	Morphing	[124]
Building stock	Switzerland	National heating and cooling; Population growth and cooling device uptake	Office/Residential/Service	RCP2.6/RCP4.5/RCP8.5	Morphing	[42]
Building stock	38 European cities	Heating and cooling; TC	Residential	RCP2.6/RCP4.5/RCP8.5	Dynamical downscaling	[22]
Building stock/ECM	Switzerland	(Peak) cooling energy demand; ECM (NV and shading)	Residential	RCP4.5	Morphing	[125]
Building stock/ECM	Luxembourg/Italy	Heating and cooling; TC; GHG emissions; ECM (green roofs)	Residential	A2	CCWorldWeatherGen	[126]

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Focus	Region	Scope	Building type	Future scenarios	Methods/Tools for generating future weather	Ref
Building/ National level	Mexico	CDH; air conditioning consumption	Residential	RCP4.5/RCP8.5	Meteonorm	[127]
Building optimization	China (Hong Kong)	Multi-objective optimization (LCC, LCGHGE, operational energy)	Residential	RCP4.5/RCP8.5	Morphing	[128]
Building optimization	Singapore	Cooling; Optimization (UDI, cooling and predicted mean vote); Point block and slab block buildings	Residential	SSP2-4.5	Morphing	[64]
Building optimization	UK	Electricity and heating; Optimal building retrofitting solution; LCC	Educational/ Office	RCP8.5	/	[129]
Building optimization	Iran	Heating gas and cooling electricity; TC; Construction cost	Educational	A2	CCWorldWeatherGen	[130]
Building optimization	Morocco	Heating and cooling; Dynamic LCC; ECM optimization	/	RCP4.5	Meteonorm	[131]
Building optimization	Australia	Heating and cooling; Energy optimization; Three building load scenarios	Office	A2	CCWorldWeatherGen	[13]
Building optimization	China	Lifespan building energy optimization (Green roof and NV)	Office	SSP1-2.6/SSP2-4.5/SSP3-7.0/ SSP5-8.5	Epwshiftr	[132]
Building optimization	Norway/Denmark	GHG emissions; Sensitivity analysis	Residential	RCP8.5	Downscaling	[83]
Building optimization	China	Multi-objective optimization	Educational	RCP4.5/RCP8.5	Morphing	[133]
Building optimization	Vietnam/Malaysia/ Thailand	Multi-objective optimization	Office	RCP4.5/RCP8.5	WeatherShift	[134]
Building optimization	Ghana	Multi-objective optimization (GWP, CED, Cost)	Residential	RCP2.6/ RCP4.5/ RCP6.0/RCP8.5	Morphing	[135]

NV: natural ventilation; TC: thermal comfort; LCGHGE: life cycle GHG emissions; LCC: life cycle cost; PV: photovoltaic; CDH: cooling degree hour; UDI: Useful Daylight Illuminance; ECM: Energy conservation measures; WWR: window to wall ratio; UHI: urban heat island; PCM: phase change material.
For building retrofit and design that investigated parameter changes are listed as Building ECM here.

Data availability

No data was used for the research described in the article.

References

[1] Hong T, Malik J, Krelling A, O'Brien W, Sun K, Lamberts R, Wei M. Ten questions concerning thermal resilience of buildings and occupants for climate adaptation. Build Environ 2023:110806. https://doi.org/10.1016/j.buildenv.2023.110806.

[2] Moazami A, Nik VM, Carlucci S, Geving S. Impacts of future weather data typology on building energy performance – investigating long-term patterns of climate change and extreme weather conditions. Appl Energy 2019;238:696–720. https://doi.org/10.1016/j.apenergy.2019.01.085.

[3] Ciancio V, Salata F, Falasca S, Curci G, Golasi I, de Wilde P. Energy demands of buildings in the framework of climate change: an investigation across Europe. Sustain Cities Soc 2020;60:102213. https://doi.org/10.1016/j.scs.2020.102213.

[4] Jalali Z, Shamseldin AY, Ghaffarianhoseini A. Impact assessment of climate change on energy performance and thermal load of residential buildings in New Zealand. Build Environ 2023:110627. https://doi.org/10.1016/j.buildenv.2023.110627.

[5] Bureau of Meteorology, State of the Climate 2022, (n.d.). http://www.bom.gov.au/state-of-the-climate/(accessed May 8, 2024).

[6] Berardi U, Jafarpur P. Assessing the impact of climate change on building heating and cooling energy demand in Canada. Renew Sustain Energy Rev 2020;121:109681. https://doi.org/10.1016/j.rser.2019.109681.

[7] de Wilde P, Coley D. The implications of a changing climate for buildings. Build Environ 2012;55:1–7. https://doi.org/10.1016/j.buildenv.2012.03.014.

[8] Andrić I, Koc M, Al-Ghamdi SG. A review of climate change implications for built environment: impacts, mitigation measures and associated challenges in developed and developing countries. J Clean Prod 2019;211:83–102. https://doi.org/10.1016/j.jclepro.2018.11.128.

[9] Yassaghi H, Hoque S. An overview of climate change and building energy: performance, responses and uncertainties. Buildings 2019;9:166. https://doi.org/10.3390/buildings9070166.

[10] Campagna LM, Fiorito F. On the impact of climate change on building energy consumptions: a meta-analysis. Energies 2022;15:354. https://doi.org/10.3390/en15010354.

[11] Abolhassani SS, Mastani Joybari M, Hosseini M, Parsaee M, Eicker U. A systematic methodological framework to study climate change impacts on heating and cooling demands of buildings. J Build Eng 2023;63:105428. https://doi.org/10.1016/j.jobe.2022.105428.

[12] Azimi Fereidani N, Rodrigues E, Gaspar AR. A review of the energy implications of passive building design and active measures under climate change in the Middle East. J Clean Prod 2021;305:127152. https://doi.org/10.1016/j.jclepro.2021.127152.

[13] Bamdad K, Cholette ME, Omrani S, Bell J. Future energy-optimised buildings — addressing the impact of climate change on buildings. Energy Build 2021;231:110610. https://doi.org/10.1016/j.enbuild.2020.110610.

[14] Karimpour M, Belusko M, Xing K, Boland J, Bruno F. Impact of climate change on the design of energy efficient residential building envelopes. Energy Build 2015;87:142–54. https://doi.org/10.1016/j.enbuild.2014.10.064.

[15] Bamdad K. Cool roofs: a climate change mitigation and adaptation strategy for residential buildings. Build Environ 2023;236:110271. https://doi.org/10.1016/j.buildenv.2023.110271.

[16] Bell NO, Bilbao JI, Kay M, Sproul AB. Future climate scenarios and their impact on heating, ventilation and air-conditioning system design and performance for commercial buildings for 2050. Renew Sustain Energy Rev 2022;162:112363. https://doi.org/10.1016/j.rser.2022.112363.

[17] Wang X, Chen D, Ren Z. Assessment of climate change impact on residential building heating and cooling energy requirement in Australia. Build Environ 2010;45:1663–82. https://doi.org/10.1016/j.buildenv.2010.01.022.

[18] Daly D, Cooper P, Ma Z. Implications of global warming for commercial building retrofitting in Australian cities. Build Environ 2014;74:86–95. https://doi.org/10.1016/j.buildenv.2014.01.008.

[19] Climate Change – Impact on Building Design and Energy - DCCEEW, (n.d.).. https://www.dcceew.gov.au/energy/publications/climate-change-impact-building-design-and-energy (accessed June 28, 2024).

[20] Li DHW, Yang L, Lam JC. Impact of climate change on energy use in the built environment in different climate zones – a review. Energy 2012;42:103–12. https://doi.org/10.1016/j.energy.2012.03.044.

[21] Trzaska S, Schnarr E. A review of downscaling methods for climate change projections. United States Agency for International Development by Tetra Tech ARD; 2014. p. 1–42.

[22] Yang Y, Javanroodi K, Nik VM. Climate change and energy performance of European residential building stocks – a comprehensive impact assessment using climate big data from the coordinated regional climate downscaling experiment. Appl Energy 2021;298:117246. https://doi.org/10.1016/j.apenergy.2021.117246.

[23] Belcher S, Hacker J, Powell D. Constructing design weather data for future climates. Build Serv Eng Res Tecnol 2005;26:49–61. https://doi.org/10.1191/0143624405bt112oa.

[24] Guan L. Preparation of future weather data to study the impact of climate change on buildings. Build Environ 2009;44:793–800. https://doi.org/10.1016/j.buildenv.2008.05.021.

[25] Jentsch MF, James PAB, Bourikas L, Bahaj AS. Transforming existing weather data for worldwide locations to enable energy and building performance simulation under future climates. Renew Energy 2013;55:514–24. https://doi.org/10.1016/j.renene.2012.12.049.

[26] Dickinson R, Brannon B. Generating future weather files for resilience. In: Proceedings of the international conference on passive and low energy architecture; 2016. p. 11–3. Los Angeles, CA, USA.
[27] Remund J, Müller S, Schilter C, Rihm B. The use of Meteonorm weather generator for climate change studies. EMS Annu. Meet. Abstr. 2010;7.
[28] Rodrigues E, Fernandes MS, Carvalho D. Future weather generator for building performance research: an open-source morphing tool and an application. Build Environ 2023;233:110104. https://doi.org/10.1016/j.buildenv.2023.110104.
[29] Jalali Z, Shamseldin AY, Ghaffarianhoseini A. Impact assessment of climate change on energy performance and thermal load of residential buildings in New Zealand. Build Environ 2023;243:110627. https://doi.org/10.1016/j.buildenv.2023.110627.
[30] D'Agostino D, Parker D, Epifani I, Crawley D, Lawrie L. How will future climate impact the design and performance of nearly zero energy buildings (NZEBs)? Energy 2022;240:122479. https://doi.org/10.1016/j.energy.2021.122479.
[31] Cellura M, Guarino F, Longo S, Tumminia G. Climate change and the building sector: modelling and energy implications to an office building in southern Europe. Energy for Sustainable Development 2018;45:46–65. https://doi.org/10.1016/j.esd.2018.05.001.
[32] Roetzel A, Tsangrassoulis A, Dietrich U. Impact of building design and occupancy on office comfort and energy performance in different climates. Build Environ 2014;71:165–75. https://doi.org/10.1016/j.buildenv.2013.10.001.
[33] Martins NR, Bourne-Webb PJ. An assessment of the potential effect of climate change on renewable hybrid heating and cooling systems. J Build Eng 2023;64:105598. https://doi.org/10.1016/j.jobe.2022.105598.
[34] Khawaja SA, Memon SA. Novel indicators to evaluate PCM performance under different ventilation strategies by considering the impact of climate change. J Build Eng 2023;74:106848. https://doi.org/10.1016/j.jobe.2023.106848.
[35] Pajek L, Potočnik J, Košir M. The effect of a warming climate on the relevance of passive design measures for heating and cooling of European single-family detached buildings. Energy Build 2022;261:111947. https://doi.org/10.1016/j.enbuild.2022.111947.
[36] Guarino F, Tumminia G, Longo S, Cellura M, Cusenza MA. An integrated building energy simulation early—design tool for future heating and cooling demand assessment. Energy Rep 2022;8:10881–94. https://doi.org/10.1016/j.egyr.2022.08.224.
[37] Nik VM. Making energy simulation easier for future climate – synthesizing typical and extreme weather data sets out of regional climate models (RCMs). Appl Energy 2016;177:204–26. https://doi.org/10.1016/j.apenergy.2016.05.107.
[38] Salvati A, Kolokotroni M. Urban microclimate and climate change impact on the thermal performance and ventilation of multi-family residential buildings. Energy Build 2023;294:113224. https://doi.org/10.1016/j.enbuild.2023.113224.
[39] Xu P, Huang YJ, Miller N, Schlegel N, Shen P. Impacts of climate change on building heating and cooling energy patterns in California. Energy 2012;44:792–804. https://doi.org/10.1016/j.energy.2012.05.013.
[40] Wang H, Chen Q. Impact of climate change heating and cooling energy use in buildings in the United States. Energy Build 2014;82:428–36. https://doi.org/10.1016/j.enbuild.2014.07.034.
[41] Deng Z, Javanroodi K, Nik VM, Chen Y. Using urban building energy modeling to quantify the energy performance of residential buildings under climate change. Build Simulat 2023. https://doi.org/10.1007/s12273-023-1032-2.
[42] Mutschler R, Rüdisüli M, Heer P, Eggimann S. Benchmarking cooling and heating energy demands considering climate change, population growth and cooling device uptake. Appl Energy 2021;288:116636. https://doi.org/10.1016/j.apenergy.2021.116636.
[43] Yu C, Pan W, Bai Y. Sensitivities of energy use reduction in subtropical high-rise office buildings: a Hong Kong case. Energy Build 2024;311:114117. https://doi.org/10.1016/j.enbuild.2024.114117.
[44] Chen X, Yang H, Zhang W. A comprehensive sensitivity study of major passive design parameters for the public rental housing development in Hong Kong. Energy 2015;93:1804–18. https://doi.org/10.1016/j.energy.2015.10.061.
[45] Qin H, Pan W. Energy use of subtropical high-rise public residential buildings and impacts of energy saving measures. J Clean Prod 2020;254:120041. https://doi.org/10.1016/j.jclepro.2020.120041.
[46] Invidiata A, Ghisi E. Impact of climate change on heating and cooling energy demand in houses in Brazil. Energy Build 2016;130:20–32. https://doi.org/10.1016/j.enbuild.2016.07.067.
[47] Waddicor DA, Fuentes E, Sisó L, Salom J, Favre B, Jiménez C, Azar M. Climate change and building ageing impact on building energy performance and mitigation measures application: a case study in Turin, northern Italy. Build Environ 2016;102:13–25. https://doi.org/10.1016/j.buildenv.2016.03.003.
[48] Radhi H. Evaluating the potential impact of global warming on the UAE residential buildings – a contribution to reduce the CO2 emissions. Build Environ 2009;44:2451–62. https://doi.org/10.1016/j.buildenv.2009.04.006.
[49] Wan KKW, Li DHW, Pan W, Lam JC. Impact of climate change on building energy use in different climate zones and mitigation and adaptation implications. Appl Energy 2012;97:274–82. https://doi.org/10.1016/j.apenergy.2011.11.048.
[50] Tian W, De Wilde P. Uncertainty and sensitivity analysis of building performance using probabilistic climate projections: a UK case study. Autom ConStruct 2011;20:1096–109. https://doi.org/10.1016/j.autcon.2011.04.011.
[51] Pérez-Andreu V, Aparicio-Fernández C, Martínez-Ibernón A, Vivancos J-L. Impact of climate change on heating and cooling energy demand in a residential building in a Mediterranean climate. Energy 2018;165:63–74. https://doi.org/10.1016/j.energy.2018.09.015.
[52] Huang K-T, Hwang R-L. Future trends of residential building cooling energy and passive adaptation measures to counteract climate change: the case of Taiwan. Appl Energy 2016;184:1230–40. https://doi.org/10.1016/j.apenergy.2015.11.008.
[53] Daniel J, Daniel S, Dev VB. Modelling & sensitivity analysis - NCC section J revision. https://ncc.abcb.gov.au/resource/report/modelling-and-sensitivity-analysis; 2018.
[54] Ayanleye S, Udele K, Nasir V, Zhang X, Militz H. Durability and protection of mass timber structures: a review. J Build Eng 2022;46:103731. https://doi.org/10.1016/j.jobe.2021.103731.
[55] Ramage MH, Burridge H, Busse-Wicher M, Fereday G, Reynolds T, Shah DU, Wu G, Yu L, Fleming P, Densley-Tingley D, Allwood J, Dupree P, Linden PF, Scherman O. The wood from the trees: the use of timber in construction. Renew Sustain Energy Rev 2017;68:333–59. https://doi.org/10.1016/j.rser.2016.09.107.
[56] Younis A, Dodoo A. Cross-laminated timber for building construction: a life-cycle-assessment overview. J Build Eng 2022;52:104482. https://doi.org/10.1016/j.jobe.2022.104482.
[57] Bamdad K, Matour S, Izadyar N, Omrani S. Impact of climate change on energy saving potentials of natural ventilation and ceiling fans in mixed-mode buildings. Build Environ 2022;209:108662. https://doi.org/10.1016/j.buildenv.2021.108662.
[58] New South Wales Government, Handbook Estimating NABERS ratings, (n.d.).. https://www.nabers.gov.au/sites/default/files/2022-11/Handbook%20for%20estimating%20NABERS%20ratings.pdf.
[59] Australian Building Codes Board. National construction code 2022. https://ncc.abcb.gov.au/. [Accessed 7 January 2025].
[60] Chakraborty D, Alam A, Chaudhuri S, Başağaoğlu H, Sulbaran T, Langar S. Scenario-based prediction of climate change impacts on building cooling energy consumption with explainable artificial intelligence. Appl Energy 2021;291:116807. https://doi.org/10.1016/j.apenergy.2021.116807.
[61] Fereidani NA, Rodrigues E, Gaspar AR. The effectiveness of the Iranian building code in mitigating climate change in Bandar Abbas. Energy for Sustainable Development 2023;76:101266. https://doi.org/10.1016/j.esd.2023.101266.
[62] Rodrigues E, Fereidani NA, Fernandes MS, Gaspar AR. Climate change and ideal thermal transmittance of residential buildings in Iran. J Build Eng 2023;74:106919. https://doi.org/10.1016/j.jobe.2023.106919.
[63] Xiong J, Guo S, Wu Y, Yan D, Xiao C, Lu X. Predicting the response of heating and cooling demands of residential buildings with various thermal performances in China to climate change. Energy 2023;269:126789. https://doi.org/10.1016/j.energy.2023.126789.
[64] Yan H, Ji G, Yan K. Data-driven prediction and optimization of residential building performance in Singapore considering the impact of climate change. Build Environ 2022;226:109735. https://doi.org/10.1016/j.buildenv.2022.109735.
[65] Hausfather Z, Peters GP. Emissions – the 'business as usual' story is misleading. Nature 2020;577:618–20. https://doi.org/10.1038/d41586-020-00177-3.
[66] Nik VM, Sasic Kalagasidis A. Impact study of the climate change on the energy performance of the building stock in Stockholm considering four climate uncertainties. Build Environ 2013;60:291–304. https://doi.org/10.1016/j.buildenv.2012.11.005.
[67] Chai J, Huang P, Sun Y. Investigations of climate change impacts on net-zero energy building lifecycle performance in typical Chinese climate regions. Energy 2019;185:176–89. https://doi.org/10.1016/j.energy.2019.07.055.
[68] Hosseini M, Javanroodi K, Nik VM. High-resolution impact assessment of climate change on building energy performance considering extreme weather events and microclimate – investigating variations in indoor thermal comfort and degree-days. Sustain Cities Soc 2022;78:103634. https://doi.org/10.1016/j.scs.2021.103634.
[69] Ukey R, Rai AC. Impact of global warming on heating and cooling degree days in major Indian cities. Energy Build 2021;244:111050. https://doi.org/10.1016/j.enbuild.2021.111050.
[70] Tootkaboni MP, Ballarini I, Corrado V. Analysing the future energy performance of residential buildings in the most populated Italian climatic zone: a study of climate change impacts. Energy Rep 2021;7:8548–60. https://doi.org/10.1016/j.egyr.2021.04.012.
[71] Chen S, Ren Z, Tang Z, Zhuo X. Long-term prediction of weather for analysis of residential building energy consumption in Australia. Energies 2021;14:4805. https://doi.org/10.3390/en14164805.
[72] Rahif R, Norouziasas A, Elnagar E, Doutreloup S, Pourkiaei SM, Amaripadath D, Romain A-C, Fettweis X, Attia S. Impact of climate change on nearly zero-energy dwelling in temperate climate: time-integrated discomfort, HVAC energy performance, and GHG emissions. Build Environ 2022;223:109397. https://doi.org/10.1016/j.buildenv.2022.109397.
[73] Liu S, Wang Y, Liu X, Yang L, Zhang Y, He J. How does future climatic uncertainty affect multi-objective building energy retrofit decisions? Evidence from residential buildings in subtropical Hong Kong. Sustain Cities Soc 2023;92:104482. https://doi.org/10.1016/j.scs.2023.104482.
[74] Tootkaboni MP, Ballarini I, Zinzi M, Corrado V. A comparative analysis of different future weather data for building energy performance simulation. Climate 2021;9:37. https://doi.org/10.3390/cli9020037.
[75] Tamer T, Gürsel Dino I, Meral Akgül C. Data-driven, long-term prediction of building performance under climate change: building energy demand and BIPV energy generation analysis across '. Renew Sustain Energy Rev 2022;162:112396. https://doi.org/10.1016/j.rser.2022.112396.
[76] Jafarpur P, Berardi U. Effects of climate changes on building energy demand and thermal comfort in Canadian office buildings adopting different temperature

setpoints. J Build Eng 2021;42:102725. https://doi.org/10.1016/j.jobe.2021.102725.
[77] Australia's emissions projections 2023 - DCCEEW, (n.d.).. https://www.dcceew.gov.au/climate-change/publications/australias-emissions-projections-2023 (accessed June 1, 2024).
[78] Duan Z. Impact of climate change on the life cycle greenhouse gas emissions of cross-laminated timber and reinforced concrete buildings in China. J Clean Prod 2023;395:136446. https://doi.org/10.1016/j.jclepro.2023.136446.
[79] Shanbhag SS, Dixit MK. Integrating evolving energy economy scenarios in dynamic life cycle assessment of buildings. Environ Impact Assess Rev 2025;112:107772. https://doi.org/10.1016/j.eiar.2024.107772.
[80] Su X, Huang Y, Chen C, Xu Z, Tian S, Peng L. A dynamic life cycle assessment model for long-term carbon emissions prediction of buildings: a passive building as case study. Sustain Cities Soc 2023;96:104636. https://doi.org/10.1016/j.scs.2023.104636.
[81] Cirrincione L, Marvuglia A, Scaccianoce G. Assessing the effectiveness of green roofs in enhancing the energy and indoor comfort resilience of urban buildings to climate change: Methodology proposal and application. Build Environ 2021;205:108198. https://doi.org/10.1016/j.buildenv.2021.108198.
[82] Shibuya T, Croxford B. The effect of climate change on office building energy consumption in Japan. Energy Build 2016;117:149–59. https://doi.org/10.1016/j.enbuild.2016.02.023.
[83] Gaarder JE, Friis NK, Larsen IS, Time B, Møller EB, Kvande T. Optimization of thermal insulation thickness pertaining to embodied and operational GHG emissions in cold climates – future and present cases. Build Environ 2023;234:110187. https://doi.org/10.1016/j.buildenv.2023.110187.
[84] Röck M, Saade MRM, Balouktsi M, Rasmussen FN, Birgisdottir H, Frischknecht R, Habert G, Lützkendorf T, Passer A. Embodied GHG emissions of buildings – the hidden challenge for effective climate change mitigation. Appl Energy 2020;258:114107. https://doi.org/10.1016/j.apenergy.2019.114107.
[85] Gupta R, Gregg M. Using UK climate change projections to adapt existing English homes for a warming climate. Build Environ 2012;55:20–42. https://doi.org/10.1016/j.buildenv.2012.01.014.
[86] Berger T, Amann C, Formayer H, Korjenic A, Pospichal B, Neururer C, Smutny R. Impacts of external insulation and reduced internal heat loads upon energy demand of offices in the context of climate change in Vienna, Austria. J Build Eng 2016;5:86–95. https://doi.org/10.1016/j.jobe.2015.11.005.
[87] Wan KKW, Li DHW, Lam JC. Assessment of climate change impact on building energy use and mitigation measures in subtropical climates. Energy 2011;36:1404–14. https://doi.org/10.1016/j.energy.2011.01.033.
[88] Kolokotroni M, Ren X, Davies M, Mavrogianni A. London's urban heat island: impact on current and future energy consumption in office buildings. Energy Build 2012;47:302–11. https://doi.org/10.1016/j.enbuild.2011.12.019.
[89] Santamouris M. Cooling the buildings – past, present and future. Energy Build 2016;128:617–38. https://doi.org/10.1016/j.enbuild.2016.07.034.
[90] Barea G, Victoria Mercado M, Filippín C, Monteoliva JM, Villalba A. New paradigms in bioclimatic design toward climatic change in arid environments. Energy Build 2022;266:112100. https://doi.org/10.1016/j.enbuild.2022.112100.
[91] Baglivo C, Congedo PM, Murrone G, Lezzi D. Long-term predictive energy analysis of a high-performance building in a mediterranean climate under climate change. Energy 2022;238:121641. https://doi.org/10.1016/j.energy.2021.121641.
[92] Santamouris M. On the energy impact of urban heat island and global warming on buildings. Energy Build 2014;82:100–13. https://doi.org/10.1016/j.enbuild.2014.07.022.
[93] Khourchid AM, Al-Ansari TA, Al-Ghamdi SG. Cooling energy and climate change nexus in arid climate and the role of energy transition. Buildings 2023;13:836. https://doi.org/10.3390/buildings13040836.
[94] Ramon D, Allacker K, Trigaux D, Wouters H, Van Lipzig NPM. Dynamic modelling of operational energy use in a building LCA: a case study of a Belgian office building. Energy Build 2023;278:112634. https://doi.org/10.1016/j.enbuild.2022.112634.
[95] Zou Y, Deng Y, Xia D, Lou S, Yang X, Huang Y, Guo J, Zhong Z. Comprehensive analysis on the energy resilience performance of urban residential sector in hot-humid area of China under climate change. Sustain Cities Soc 2023;88:104233. https://doi.org/10.1016/j.scs.2022.104233.
[96] Phillips R, Fannon D, Eckelman MJ. Dynamic modeling of future climatic and technological trends on life cycle global warming impacts and occupant satisfaction in US office buildings. Energy Build 2022;256:111705. https://doi.org/10.1016/j.enbuild.2021.111705.
[97] Ma Y, Zedan S, Liu A, Miller W. Impact of a warming climate on hospital energy use and decarbonization: an Australian building simulation study. Buildings 2022;12:1275. https://doi.org/10.3390/buildings12081275.
[98] Wang R, Lu S, Zhai X, Feng W. The energy performance and passive survivability of high thermal insulation buildings in future climate scenarios. Build Simulat 2022;15:1209–25. https://doi.org/10.1007/s12273-021-0818-3.
[99] Ascione F, De Masi RF, Gigante A, Vanoli GP. Resilience to the climate change of nearly zero energy-building designed according to the EPBD recast: monitoring, calibrated energy models and perspective simulations of a Mediterranean nZEB living lab. Energy Build 2022;262:112004. https://doi.org/10.1016/j.enbuild.2022.112004.
[100] Kim D, Cho H, Mago PJ, Yoon J, Lee H. Impact on renewable design requirements of net-zero carbon buildings under potential future climate scenarios. Climate 2021;9:17. https://doi.org/10.3390/cli9010017.
[101] Ismail FH, Shahrestani M, Vahdati M, Boyd P, Donyavi S. Climate change and the energy performance of buildings in the future – a case study for prefabricated buildings in the UK. J Build Eng 2021;39:102285. https://doi.org/10.1016/j.jobe.2021.102285.
[102] Tsoka S, Velikou K, Tolika K, Tsikaloudaki A. Evaluating the combined effect of climate change and urban microclimate on buildings' heating and cooling energy demand in a mediterranean city. Energies 2021;14:5799. https://doi.org/10.3390/en14185799.
[103] Hasan A, Bahadori-Jahromi A, Mylona A, Ferri M, Tahayori H. Investigating the potential impact of future climate change on UK supermarket building performance. Sustainability 2021;13:33. https://doi.org/10.3390/su13010033.
[104] Bazazzadeh H, Pilechiha P, Nadolny A, Mahdavinejad M, sara Hashemi safaei S. The impact assessment of climate change on building energy consumption in Poland. Energies 2021;14:4084. https://doi.org/10.3390/en14144084.
[105] Triana MA, Lamberts R, Sassi P. Sustainable energy performance in Brazilian social housing: a proposal for a Sustainability Index in the energy life cycle considering climate change. Energy Build 2021;242:110845. https://doi.org/10.1016/j.enbuild.2021.110845.
[106] Fajilla G, Borri E, De Simone M, Cabeza LF, Bragança L. Effect of climate change and occupant behaviour on the environmental impact of the heating and cooling systems of a real apartment. A parametric study through life cycle assessment. Energies 2021;14:8356. https://doi.org/10.3390/en14248356.
[107] Pajek L, Košir M. Strategy for achieving long-term energy efficiency of European single-family buildings through passive climate adaptation. Appl Energy 2021;297:117116. https://doi.org/10.1016/j.apenergy.2021.117116.
[108] Akkose G, Meral Akgul C, Dino IG. Educational building retrofit under climate change and urban heat island effect. J Build Eng 2021;40:102294. https://doi.org/10.1016/j.jobe.2021.102294.
[109] Pajek L, Jevrić M, Ćipranić I, Košir M. A multi-aspect approach to energy retrofitting under global warming: a case of a multi-apartment building in Montenegro. J Build Eng 2023;63:105462. https://doi.org/10.1016/j.jobe.2022.105462.
[110] Thapa S, Rijal HB, Pasut W, Singh R, Indraganti M, Bansal AK, Panda GK. Simulation of thermal comfort and energy demand in buildings of sub-Himalayan eastern India - impact of climate change at mid (2050) and distant (2080) future. J Build Eng 2023;68:106068. https://doi.org/10.1016/j.jobe.2023.106068.
[111] Amaripadath D, Rahif R, Zuo W, Velickovic M, Voglaire C, Attia S. Climate change sensitive sizing and design for nearly zero-energy office building systems in Brussels. Energy Build 2023;286:112971. https://doi.org/10.1016/j.enbuild.2023.112971.
[112] Nunes G, Giglio T. Effects of climate change in the thermal and energy performance of low-income housing in Brazil—assessing design variable sensitivity over the 21st century. Renew Sustain Energy Rev 2022;168:112885. https://doi.org/10.1016/j.rser.2022.112885.
[113] Roshan G, Moghbel M, Farrokhzad M. Mitigation of climate change impact using green wall and green roof strategies: comparison between two different climate regions in Iran. Theor Appl Climatol 2022;150:167–84. https://doi.org/10.1007/s00704-022-04146-w.
[114] Kharbouch Y. Effectiveness of phase change material in improving the summer thermal performance of an office building under future climate conditions: an investigation study for the Moroccan Mediterranean climate zone. J Energy Storage 2022;54:105253. https://doi.org/10.1016/j.est.2022.105253.
[115] Zou Y, Xiang K, Zhan Q, Li Z. A simulation-based method to predict the life cycle energy performance of residential buildings in different climate zones of China. Build Environ 2021;193:107663. https://doi.org/10.1016/j.buildenv.2021.107663.
[116] Ferdyn-Grygierek J, Sarna I, Grygierek K. Effects of climate change on thermal comfort and energy demand in a single-family house in Poland. Buildings 2021;11:595. https://doi.org/10.3390/buildings11120595.
[117] Verichev K, Zamorano M, Fuentes-Sepúlveda A, Cárdenas N, Carpio M. Adaptation and mitigation to climate change of envelope wall thermal insulation of residential buildings in a temperate oceanic climate. Energy Build 2021;235:110719. https://doi.org/10.1016/j.enbuild.2021.110719.
[118] Nurlybekova G, Memon SA, Adilkhanova I. Quantitative evaluation of the thermal and energy performance of the PCM integrated building in the subtropical climate zone for current and future climate scenarios. Energy 2021;219:119587. https://doi.org/10.1016/j.energy.2020.119587.
[119] Heracleous C, Michael A, Savvides A, Hayles C. Climate change resilience of school premises in Cyprus: an examination of retrofit approaches and their implications on thermal and energy performance. J Build Eng 2021;44:103358. https://doi.org/10.1016/j.jobe.2021.103358.
[120] Hao L, Herrera-Avellanosa D, Del Pero C, Troi A. Overheating risks and adaptation strategies of energy retrofitted historic buildings under the impact of climate change: case studies in alpine region. Appl Sci 2022;12:7162. https://doi.org/10.3390/app12147162.
[121] De Masi RF, Festa V, Gigante A, Mastellone M, Ruggiero S, Vanoli GP. Effect of climate changes on renewable production in the mediterranean climate: case study of the energy retrofit for a detached house. Sustainability 2021;13:8793. https://doi.org/10.3390/su13168793.
[122] Ahmadian E, Bingham C, Elnokaly A, Sodagar B, Verhaert I. Impact of climate change and technological innovation on the energy performance and built form of future cities. Energies 2022;15:8592. https://doi.org/10.3390/en15228592.
[123] Bass B, New J. How will United States commercial building energy use be impacted by IPCC climate scenarios? Energy 2023;263:125945. https://doi.org/10.1016/j.energy.2022.125945.

[124] Hietaharju P, Pulkkinen J, Ruusunen M, Louis J-N. A stochastic dynamic building stock model for determining long-term district heating demand under future climate change. Appl Energy 2021;295:116962. https://doi.org/10.1016/j.apenergy.2021.116962.

[125] Silva R, Eggimann S, Fierz L, Fiorentini M, Orehounig K, Baldini L. Opportunities for passive cooling to mitigate the impact of climate change in Switzerland. Build Environ 2022;208:108574. https://doi.org/10.1016/j.buildenv.2021.108574.

[126] Cirrincione L, Marvuglia A, Scaccianoce G. Assessing the effectiveness of green roofs in enhancing the energy and indoor comfort resilience of urban buildings to climate change: Methodology proposal and application. Build Environ 2021;205:108198. https://doi.org/10.1016/j.buildenv.2021.108198.

[127] Jiménez Torres M, Bienvenido-Huertas D, May Tzuc O, Bassam A, Ricalde Castellanos LJ, Flota-Bañuelos M. Assessment of climate change's impact on energy demand in Mexican buildings: projection in single-family houses based on Representative Concentration Pathways. Energy for Sustainable Development 2023;72:185–201. https://doi.org/10.1016/j.esd.2022.12.012.

[128] Liu S, Wang Y, Liu X, Yang L, Zhang Y, He J. How does future climatic uncertainty affect multi-objective building energy retrofit decisions? Evidence from residential buildings in subtropical Hong Kong. Sustain Cities Soc 2023;92:104482. https://doi.org/10.1016/j.scs.2023.104482.

[129] Luo XJ, Oyedele LO. Life cycle optimisation of building retrofitting considering climate change effects. Energy Build 2022;258:111830. https://doi.org/10.1016/j.enbuild.2022.111830.

[130] Aram K, Taherkhani R, Šimelytė A. Multistage optimization toward a nearly net zero energy building due to climate change. Energies 2022;15:983. https://doi.org/10.3390/en15030983.

[131] Kharbouch Y, Boushaba H, Ameur M. Optimisation of the insulation thickness for the external walls in Morocco while considering the effect of climate change. Therm Sci Eng Prog 2022;35:101455. https://doi.org/10.1016/j.tsep.2022.101455.

[132] Shi D, Gao Y, Zeng P, Li B, Shen P, Zhuang C. Climate adaptive optimization of green roofs and natural night ventilation for lifespan energy performance improvement in office buildings. Build Environ 2022;223:109505. https://doi.org/10.1016/j.buildenv.2022.109505.

[133] Zou Y, Lou S, Xia D, Lun IYF, Yin J. Multi-objective building design optimization considering the effects of long-term climate change. J Build Eng 2021;44:102904. https://doi.org/10.1016/j.jobe.2021.102904.

[134] Nguyen AT, Rockwood D, Doan MK, Dung Le TK. Performance assessment of contemporary energy-optimized office buildings under the impact of climate change. J Build Eng 2021;35:102089. https://doi.org/10.1016/j.jobe.2020.102089.

[135] Ansah MK, Chen X, Yang H. A holistic environmental and economic design optimization of low carbon buildings considering climate change and confounding factors. Sci Total Environ 2022;821:153442. https://doi.org/10.1016/j.scitotenv.2022.153442.