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Climate risk assessment of buildings: An analysis of operating emissions of commercial offices in Australia

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ABSTRACT

Building climate risk assessment involves benchmarking a building‘s energy use intensity against decarbonisation pathways to mitigate the impacts on climate change. Various climate risk assessment tools and frameworks are used for commercial buildings in different jurisdictions. This study reviewed 20 climate risk assessment tools based on their availability, application and underlying framework. Due to being the only available tool that sets global targets with local benchmarks in Australia to assess the risks associated with energy use in commercial offices, Carbon Risk Real Estate Monitor (CRREM) was chosen. Using the CRREM tool, 431 commercial office buildings across Australia are benchmarked and the results were compared based on climate zones, jurisdictions, locations and sustainability ratings. Results revealed that 58.2% (n = 251) of buildings met the energy use targets. Most energy-efficient offices are found in the VIC state, within the Central Business District of Melbourne. Conversely, improvement is needed in Darwin, Northern Territory. The buildings at climate risk (41.8%, n = 180) need to reduce their on-site energy intensity by an aggregated net performance gap of 5484 kWh/m^2/year in total. This significant shortfall highlights the critical imperative for all buildings to swiftly align with decarbonisation pathways, ensuring they meet 2050 climate change targets.

1. Introduction

One of the significant events related to climate change is global warming. Global warming is defined as the ongoing increase in global average temperature and its effect on Earth‘s climate [2]. Greenhouse Gas (GHG) and carbon emissions associated with human activities and influences are regarded as some of the main causes of global warming [33]. These emissions are mainly due to burning fossil fuels subsequently increasing the temperature and resulting in global warming [25]. The latest publication of the Intergovernmental Panel on Climate Change (IPCC) Synthesis Report of the Sixth Assessment Report (AR6) outlined the current status, trends, and future climate change risks. According to the report, the current average global surface temperature increase of the Earth was measured to reach 1.09°C above pre-industrial levels (1850–1900) in 2011–2020. The report finds that it was likely that GHGs contributed to a warming of 1–2°C due to climate change [29].

Climate-induced stresses, extreme weather events and natural disasters are inflicted upon the planet at an increasing rate. These events cause significant environmental, social, economic, governmental and health consequences [58]. These events happen in the form of climate hazards (e.g., heatwaves, floods, hurricanes, storms, significant precipitation), risks to ecosystems and humans (e.g., higher mortality rates, decreased wellbeing, increased inequalities, climate injustice) [52]. Significant global climate-induced events that happened in July 2023, measured as the hottest July ever ranked since global records began in 1850, are mapped in Fig. 1 [35]. Some of these events included the following:

- **America:** Canada, Peru, Brazil, and the Caribbean had its warmest July on record. July in Uruguay, the United States, and Argentina were ranked the 10th, 11th and 12th warmest, respectively.
- **Europe:** Spain recorded its sixth-warmest July and Europe has its eighth-warmest July on record.

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Nomenclature

Abbreviations

ABC	Alliance for Buildings and Construction
ASCOR	Assessing Sovereign Climate-Related Opportunities and Risks
ASEAN	The Association of Southeast Asian Nations
BBP	Better Buildings Partnership
BPIE	Buildings Performance Institute Europe
CBD	Central Business District
CBECS	Commercial Buildings Energy Consumption Survey
CDDs	Cooling Degree Days
CHSB	Cornell Hotel Sustainability Benchmarking Tool
CISL	Cambridge Institute of Sustainability Leadership
CRCLCL	Cooperative Research Centre for Low Carbon Living
CRREM	Carbon Risk Real Estate Monitor
CVAT	Carbon Value Analyser Tool
DGBC	Dutch Green Building Council
DJSI	Dow Jones Sustainability Indices
DWRI	Destination Water Risk Index
ESG	Environmental, Social and Governance
EU	European Union
EUI	Energy Use Intensity
F-gasses	Fugitive Gasses
GBCA	Green Building Council of Australia
GHG	Greenhouse Gas
GIA	Gross Internal Area
GlobalABC	Global Alliance for Buildings and Construction
GRESB	Global Real Estate Sustainability Benchmark
GRI	Global Reporting Initiative
HCMI	Hotel Carbon Management Initiative
HDDs	Heating Degree Days
IEA	International Energy Agency
INREVP	European Investors in Non-Listed Real Estate
IGCC	Institutional Investors Group on Climate Change
IPCC	Intergovernmental Panel on Climate Change
ISS	Institutional Shareholder Services
ISSB	International Sustainability Standards Board
LCI	Low Carbon Institute
LSE	London School of Economics
LETI	London Transformation Energy Initiative
NABERS	National Australian Built Environment Rating System
NAREIT	National Association of Real Estate Investment Trusts
NLA	Net Lettable Area
NZAI	Net Zero Asset Managers Initiative
NZAOA	Net Zero Asset Owner Alliance
NZE	Net Zero Emissions
NZIF	Net Zero Investment Framework
PAII	Paris Aligned Investment Initiative
PCAF	Partnership for Carbon Accounting Financials
PRI	Principles for Responsible Investment
RIBA	Royal Institute of British Architects
SASB	Sustainability Accounting Standards Board
SBTi	Science-Based Targets Initiative
STI	Sustainable Travel Index
SDA	Sectoral Decarbonisation Approach
SDGs	Sustainable Development Goals
SFDR	Sustainable Finance Disclosure Regulation
TCFD	Task Force on Climate-Related Financial Disclosures
TNFD	Task Force on Nature-Related Financial Disclosures
TPI	Transition Pathway Initiative
TSP	Target Setting Protocol
UKGBC	UK Green Building Council
ULI	Urban Land Institute
UNEP	United Nations Environment Program
WIS	World Resources Institute
WWR	Window-to-Wall Ratio
WGBC	World Green Building Council

Units of measure

°C	degrees Celsius
CO_2	carbon dioxide
CO_2e	carbon dioxide-equivalent
GHG	Greenhouse gas
GHG_e	Greenhouse gas-equivalent
$GtCO_2$	Gigatonne carbon dioxide
$GtCO_2e$	Gigatonne carbon dioxide equivalent
$kgCO_2/m^2/year$	kilogram carbon dioxide per square meter per year
$kgCO_2e/m^2/year$	kilogram carbon dioxide-equivalent per square meter
kWh	kilowatt-hour
kWh/m^2	kilowatt hour per square meter
TWh	terawatt hour
TWhe	terawatt hour-equivalent

- **Asia:** Hong Kong recorded its third-warmest July; Japan experienced the highest temperature for July since records began in 1946.
- **Oceania:** Australia had its ninth-warmest July since records began in 1910; New Zealand had its fourth-warmest July since records began in 1909.

The Paris Agreement signed among various countries in 2016 made a pledge against limiting global warming to 1.5°C and 2°C temperature increase to minimise the risks associated with climate change [54]. However, due to the current trends in the global surface temperature increase, IPCC found that limiting global warming to 1.5°C or 2°C has a very low or low possibility, respectively [29]. Rapid decarbonisation ambitions across the economy can help neutralise and ultimately reverse the impacts of climate change [6]. To do so, sectoral approaches to decarbonisation must be developed and adopted in an urgent fashion.

The building sector‘s significantly contributes to carbon emissions associated with climate change, reaching 37% globally and 21% in Australia, including emissions from the transportation and construction of buildings [53,26]. This includes both scope 1 and 2 emissions as well as a proportion of scope 3 emissions[1] (10 % of scope 3 emissions are included related to transportation and construction) [26]. This prompts international and national legislative authorities, as well as non −profit organisations to develop decarbonisation pathways and targets in line with global warming limits. These initiatives have led to the creation of

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[1] Scope 1 emissions refer to direction GHG emissions that result from sources are owned or controlled by the company, including emissions from combustion in owned boilers. Scope 2 emissions are the electricity indirect GHG emissions that usually are purchased and consumed by the company. Scope 3 emissions is defined as the other indirect emission associated with the organisation’s value chain (Protocol Greenhouse Gas, 2004).

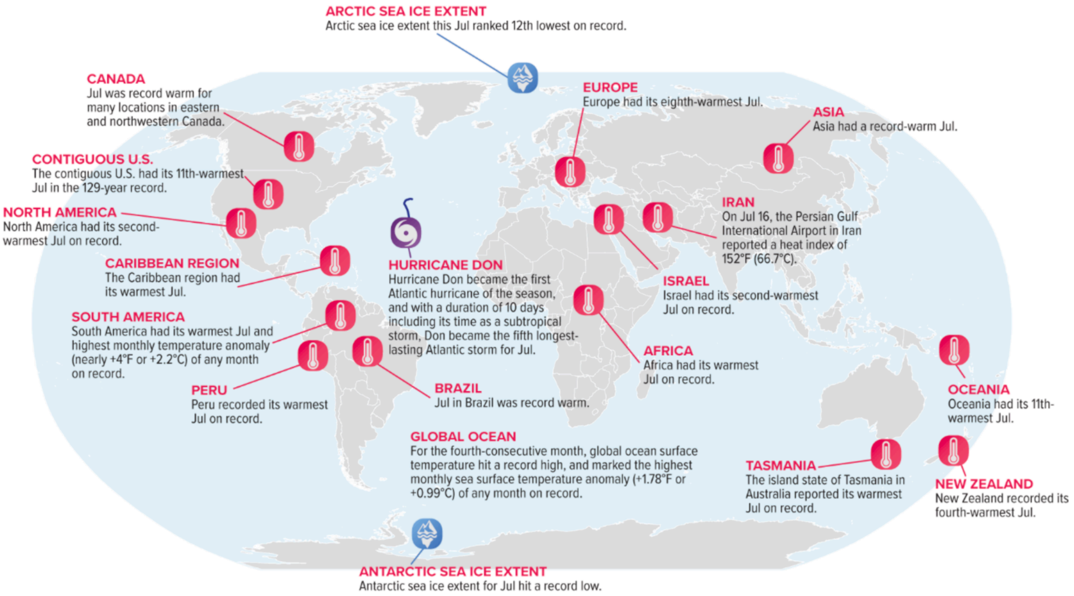

Fig. 1. Significant climate-induced extreme weather events recorded in July 2023 globally [35].

new methodologies, tools and benchmarks aimed at achieving stringent performance targets and commitments [60,61,9,3,43,32,20,24,19,40]. Meeting these targets requires a combination of top-down and bottom-up approaches, supported by industry-wide action worldwide. Several science-based climate targets, along with climate risk assessment tools and frameworks used across various jurisdictions to benchmark energy usage against established decarbonization pathways [10].

In this study 20 climate risk assessment tools are reviewed and analyzed to identify the most suitable one for the research's purpose, considering factors such as availability, application, and underlying framework. Among these tools, a novel and widely acclaimed method has emerged for the property sector named the Carbon Risk Real Estate Monitor (in short, CRREM) originally within the European Union (EU) in support of the Global Real Estate Sustainability Benchmark (GRESB) and Science-Based Targets Initiative (SBTi) [12,22,44,45]. Climate risk assessment is often performed to evaluate the risks that buildings may encounter in the face of a changing climate. However, an approach that considers the risks that buildings have on intensifying climate change impacts has not been conducted for the case of Australia. To address this research gap, the top-down climate risk assessment method is coupled with benchmarking the bottom-up performance of commercial buildings in Australia. 431 commercial office properties in various climate zones and jurisdictions across Australia were assessed with the use of the CRREM tool All office buildings have an active National Australian Built Environment Rating System (NABERS[2]) star rating [36].

An overview of the research plan is illustrated in Table 1.

In addition, the paper presents a series of climate risk performance benchmarking measures against the NABERS rating systems and climate targets, along with recommendations aimed at reducing cumulative operating emissions to close the energy performance gap of Australian offices. These findings can inform future research and contribute policy recommendations for decarbonising operational emissions in the Australian office building sector.

2. Current state in building climate risk assessment

This section delves into the climate targets for the building sector. Section 2.1 reviews the global and local climate change targets for the building sector. Section 2.2 discusses the alignment between climate targets and risk assessment processes.

2.1. *Climate targets for the building sector*

Climate risk assessment of buildings includes evaluating the risks of a building on climate change, measured in energy consumption, carbon or GHG emissions [17]. The Task Force on Climate-related Financial Disclosures (TCFD) framework established in the EU incorporates four pillars, involving (1) governance, (2) strategy, (3) risk management, and (4) metrics and targets. Within the metrics and targets pillar, TCFD outlines the significance of measuring and managing climate change-related risks and opportunities for organisations. The TCFD framework‘s metrics are applicable to the building, property and real estate sectors [48]. Addressing the TCFD framework, several decarbonisation targets and pathways for buildings are established globally and locally.

Many organisations have set local and global climate targets until 2050 to deliver net zero operational and/or embodied carbon outcomes for buildings (Fig. 2). Globally, the World Green Building Council (WGBC), C40 Global Challenges, Global Alliance for Buildings and Construction (GlobalABC) Africa and International Energy Agency (IEA), and The Association of Southeast Asian Nations (ASEAN) have set an overarching net zero whole life carbon target for all new buildings by 2050 (WGBC, 2020; 2019; [9,20,24]. Similar to the WorldGBC, the Green Building Council of Australia (GBCA) has set a net zero whole life carbon targets for new buildings by 2050, with interim targets assuring the overall goal through a net zero energy target by 2025 and 40% reduction in embodied carbon by 2040 [19]. Extending these ambitious targets, the Low Carbon Institute (LCI) and London Energy Transformation Initiative (LETI) have set a net zero whole life carbon target by 2050 for all buildings, including new builds and retrofits, for Australia and the UK, respectively [40,32]. The Royal British Institute of Architects (RIBA), following the 2030 Challenge, have set aspirational 2025 and 2030 targets for up to 60% and 40% operational and embodied carbon reductions, respectively [43].

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[2] NABERS: National Australian Built Environment Rating System is a commonly sustainability performance rating used for buildings in Australia and internationally. It provides comparable sustainability benchmarking across buildings sectors including hotels, shopping centres, data centres, commercial offices, apartments, among others. It provides a rating from one to six stars for building performance across energy, water, waste and indoor environment. The rating is valid for 12 months and it represents a building`s actual current operational performance (NABERS, 2023).

Table 1
Research plan overview.

Step	Research gap	Research aims	Research questions	Research methods	Output
STEP 1-Suitability Analysis of climate risk assessment tools	There is a need for a comprehensive analysis of the effectiveness and limitations of existing climate risk assessment tools in addressing specific contextual factors related to building performance and decarbonisation efforts.	To fill the gap, the existing climate risk assessment tools for buildings were reviewed and analysed to identify their contextual suitability.	What are the underlying methods and potential applications of building carbon risk assessment tools?	To undertake a literature review and comparative analysis of climate risk assessment tools.	Among 20 climate risk assessment tools, CRREM was selected since its contextual suitability
STEP 2- Climate Risk Evaluation for Commercial Office Buildings in Australia	There is a lack of comprehensive research that compares building performance outputs using both top-down and bottom-up approaches and evaluates their alignment with local sustainability ratings and global decarbonisation pathways.	To fill the gap, the climate risk of 431 commercial office properties in various climate zones and jurisdictions across Australia were evaluated	To what extent can the Australian commercial office buildings deliver on the global and local operating emissions reduction ambitions towards a 1.5 °C future?	To perform climate risk assessment of commercial office buildings in Australia using the CRREM tool and mapping outputs against the CRREM decarbonisation pathways.	Alignment with between local sustainability ratings and global decarbonisation pathways and required retrofit actions for those commercial offices were determined.

2.2. Alignment between climate targets and risk assessment processes

Decarbonising the built environment is a multifaceted challenge as it encompasses all phases of the construction and operation, from material production to energy-efficient building design, energy systems and occupant-building interactions. Efforts have been made to advance carbon risk assessment in the built environment, including commitments to decarbonisation, the development of frameworks, and the establishment of clearer targets and pathways. However, several challenges still exist.

Globally, there is a lack of asset-level decarbonisation target setting and climate risk assessments processes. In response to the WorldGBC's *Advancing Net Zero* ambitions which aims to achieve net-zero carbon buildings by 2030 for all new buildings and 2050 for all buildings, various local green building councils around the world *have proposed net zero transition roadmaps* [59]. However, these roadmaps primarily serve as high-level policies and lack operational and actionable measures. For example, UKGBC [51] has put forward a *Net Zero Whole Life Carbon Roadmap,* outlining a shared vision and agreed industry-wide actions for achieving net-zero carbon. The goals and visions in these policies are defined based on the entire building stock. Similarly, GBCA has proposed the *Carbon Positive Roadmap,* which established common goals in key areas, including renewable energy, low energy-intensive buildings, zero carbon materials, and transition to electric vehicles for the Australian building stock [19].

Despite these efforts, these roadmaps primarily serve as high-level policies and often lack operational and actionable measures. The goals and visions outlined in these policies are typically defined based on the entire building stock, highlighting the need for more granular asset-level decarbonization strategies and climate risk assessment processes, especially in the Australian context. For instance, characteristics related to geographic locations, such as local climate and floor area growth projection, and building typologies, such as window-to-wall ratio (WWR) and functional requirements, can influence buildings' performance and progress towards net zero. However, these factors are not often translated into decarbonisation pathways for the specific regions and building typologies. For example, the Challenge 2030 [3] established a trajectory for achieving net zero, including goals for the baseline years 2005, 2020, 2025, and 2030. However, uniform percentage-based reduction targets are proposed for all building types. The *Climate Emergency Design Guide* employed a comprehensive approach to determine energy-intensity targets for different building archetypes [32]. The approach involves considering both top-down allocation of renewable energy budget to different building types and bottom-up adjustments of energy use intensity (EUI) targets based on building characteristics informed by simulation studies. However, there is no account of how regions with different climatic characteristics can influence the target setting.

3. Research methods

The research methods of the study have been presented, focusing on the selection of the building climate risk assessment tool (in Section 3.1), analysed office buildings (in Section 3.2) and climate risk assessment method (in Section 3.3).

3.1. Selection of building climate risk assessment tool

This section reviews and comparatively analyses the commonly used climate risk assessment frameworks and tools applicable to buildings and for the use of building owners. Numerous climate risk assessment tools for climate action, provided as open source or as paid services, have been developed in academia and the industry [56]. Climate risk assessment tools that are applicable to different commercial building types with sufficient data on their underlying methodological framework and application to assess climate risks have been analysed in this section. A total of 20 climate risk assessment tools, developed either by academic, non-profit or commercial organisations, are reviewed and comparatively analysed to identify the underlying frameworks of the tools and the extent of the tool‘s practical application. The 20 climate risk assessment tools are categorised according to their underlying methodological frameworks regarding the type of disclosure, assessment method, performance output, building lifecycle stage and data coverage. In addition, these tools are categorised regarding the types of application, availability, interface, data coverage, sector, scale, applicable building types and emission scopes (Table 2).

Among these tools, the majority are available open source, with only three of them offered as a paid service. Most tools have a global coverage (n = 14), and the locally applicable ones are developed for jurisdictions within the EU, UK, Australia, and Asia. The tool interfaces vary from Microsoft Excel to website-based applications and reports. Sector-wise, tools are categorised as assessment tools for the corporate, property, infrastructure, and hospitality sectors as well as general. Of the 20 tools, 10 are suitable for the property sector. Within these sectors, a subclassification of the scale at which the tools can be used to perform climate risk assessments is determined. As such, 12 are used for asset-level assessments, of which 10 are suitable for the portfolio level as well. The remaining are mostly suitable for sectoral or company-level assessments. The tools that offer asset-level assessments specify the applicable building type which varies from residential (n = 5) to commercial (n = 6), retail (n = 3), hotel (n = 2), healthcare (n = 2) or educational (n = 1) buildings. Some tools can be used for multiple

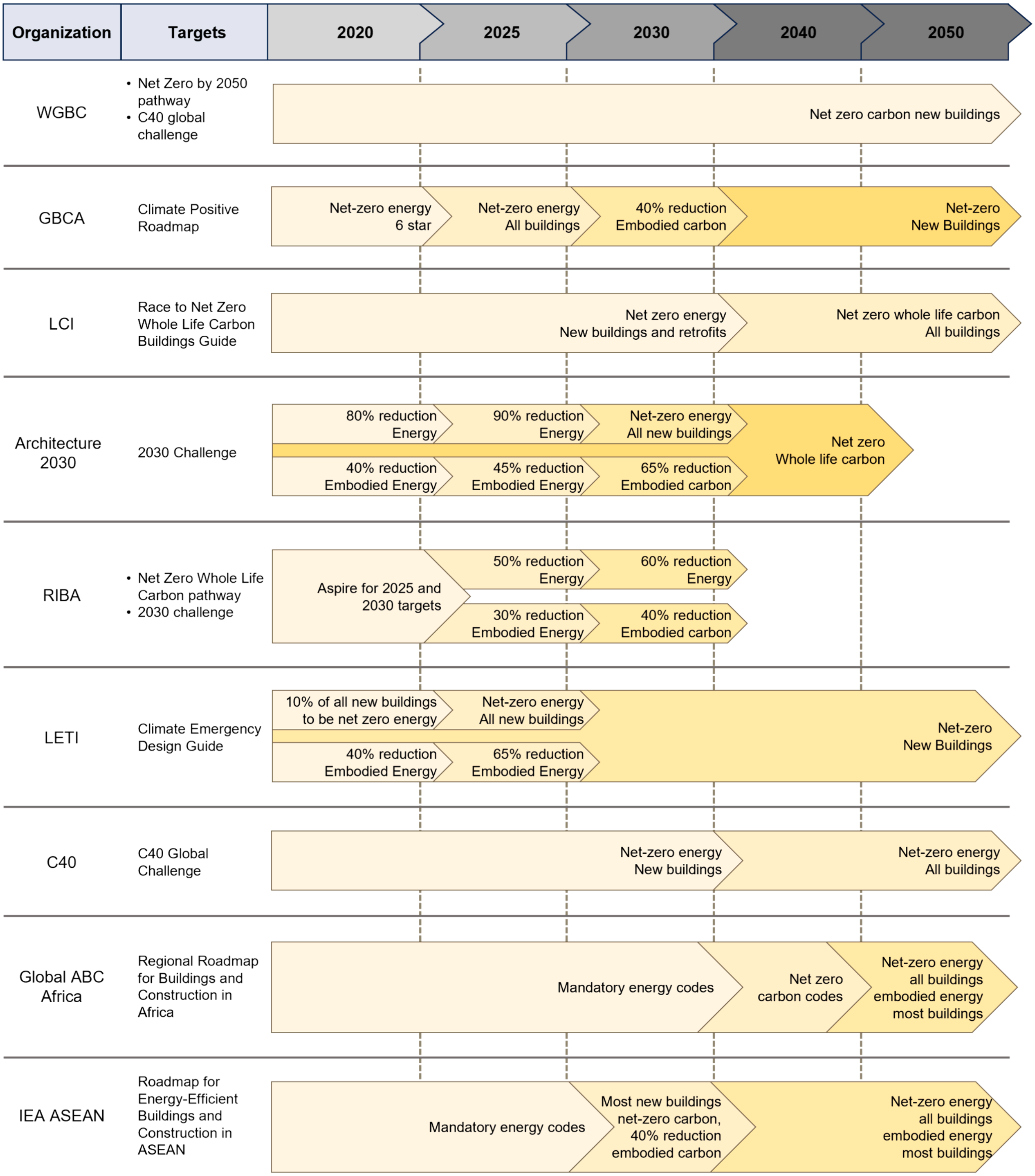

Fig. 2. Global and local climate targets in the buildings sector on a timeline.

building types (n = 5). While most tools calculate scope 1, 2 and 3 data, five tools exclude scope 3. In most cases, scope 3 emissions are considered tenancy-related emissions.

The CRREM method, its pathway and its tool (version 2.03) are selected to assess the climate risk of 431 NABERS-rated commercial office buildings in Australia in various climate zones based on the energy pathways developed as part of CRREM [13]. CRREM was selected for its relevance to the Australian context and its applicability to commercial office buildings, providing benchmarks both globally and locally. This helps align an individual building's performance with buildings of a similar nature worldwide. This tool assesses the risks associated with energy use in commercial offices, aligning with the goals outlined in the Paris Agreement to limit global warming. CRREM involves a top-down whole-of-economy process to determine decarbonisation pathways for energy consumption and operational carbon emissions for properties and portfolios across several countries to limit global warming to 1.5°C [13]. To do so, it allocates a share of the global anthropogenic carbon budget (759 $GtCO_{2e}$ or 468 $GtCO_2$) to countries, the building stock (102

Table 2
Underlying frameworks and pathway alignment of the tools. In disclosure type A: Academic, NfP: Not-for-profit, C: Commercial; V: Voluntary, M: Mandatory for signatories; in assessment method TD: Top-down, BU: Bottom-up, M: Mixed; in measured performance output E: Energy, C: Carbon, GHG: Greenhouse Gas, M: Management, SDGs: Sustainable Development Goals; in lifecycle stage O: Operational, E: Embodied; in data coverage B: Building, P: Portfolio, C: Company. In type P: Pathway, T: Tool, G: Guideline, R: Rating, F: Framework, C: Commitment, B: Benchmark; in availability OS: Open source, PS: Paid service; in interface W: Website, E: Excel, R: Report, N: Not known; in coverage G: Global, L: Local; in sector C: Corporate, P: Property, I: Infrastructure, H: Hospitality, G: General; in scale of application L: Legislation, E: Economy, S: Sector, C: Company, P: Portfolio, A: Asset; in building archetype Resi: Residential, Com: Commercial, Re: Retail, Ind: Industrial, Ho: Hotel, Heal: Healthcare, Edu: Educational, NA: Not available.

ID	Name	Reference	Organisation	Alignment with initiatives and frameworks	Disclosure type	Assessment method	Performance output	Lifecycle stage	Data coverage	Performance target	Pathway timeframe & type	Availability &Interface	Coverage &Sector	Scale	Building type	Scope
1	CRREM	[27]	A	GRESB, INREV, PCAF, TCFD, EU Taxonomy, SBTi, IEA, IPCC	V	M	E, C, GHG	O	B, P, C	Energy efficiency for limiting global warming to 1.5 °C	by 2050P, T	OS E	G, L P	C, P, A	Resi, Com, Re, Ind, Ho, Heal	1, 2, 3
2	Hotel Footprinting Tool	[21]	NfP	TCFD, NZ Government, UK Government, DWRI, Euromonitor STI, ULI Greenprint Performance Report, Hotel Global Decarbonisation Report, HCMI, CHSB	V	BU	E, GHG	O	B	NA	NAT	OS W	G H	A	Ho	1, 2
3	Hotel Energy Solutions (HES) Toolkit	[55]	NfP	Davos Process 2007, EU Commission	NA	BU	E	O	B	20 % increase in energy efficiency and 10 % in renewable energy	NAT	OS W	L (EU) H	C	NA	1, 2
4	Carbon Value Analyser Tool (CVAT)	[57]	NfP	TCFD	V	BU	GHG	O	P	NA	NAT	OS E	L P	P, A	Resi, Com	1, 2
5	GRESB ESG Benchmark	GRESB [22]	NfP	GRI, PRI, SASB, DJSI, TCFD, NAREIT	V	BU	M, E, C	O	B, P, C	NA	NAB	OS N	G P	C, P, A	Resi, Com, Re, Ind, Ho, Heal	1, 2, 3
6	SBTi Pathways		NfP	TCFD, IPCC, IEA, Net zero standard framework	V	TD	E, C, GHG, SDGs	NA	P, C	Limiting global warming to 1.5 °C, net-zero carbon and GHG emissions	by 2050P	OS N	G C,P	S, C	NA	1, 2, 3
7	Paris Proof Retail Real Estate	[8]	NfP	UNEP, GABC, IPCC, Net Zero Asset Managers Initiative	V	TD	E, C	O, E	B, P	Net zero carbon	by 2050 reported every 5 yearsC	OS N	G P	S, C, P, A	Re	1, 2, 3
8	Carbon Risk Rating	[30]	C	UN SDGs, GRI, SASB, EU Taxonomy, IEA Sustainable Development Scenario	V	BU	GHG	NA	P, C	Net zero emissions	by 2050R	PS N	G, L C	C, P	NA	1, 2, 3
9	S&P Global TruCost	[47]	C	TCFD, SBTi, EU climate transition benchmark, Paris-aligned benchmark and Low Carbon Benchmark	NA	M	E, C	NA		7 % reduction in emissions per year	By the specified date F	PS N	G C	C, P	NA	1, 2; 3*
10	Climate Risk Analysis	[34]	C	TCFD, SFDR, EU Taxonomy, SBTi	V	M	GHG	NA	C	Net zero GHG emissions	By the specified date F	PS N	L C	S, C, P	NA	1, 2, 3
11	TPI Tool	[49]	NfP	TCFD, SDA, IEA, WorldGBC	V	M	E, C	O, E	C	Limiting global warming to 1.5 °C or 2 °C	By the specified date T,F	OS N	G C	C	NA	1, 2, 3
12	Net Zero Carbon Pathway Framework	[5]	NfP	TCFD, GHG Protocol, PICC	M	M	E, C	NA	NA	45 % carbon reduction	by 2030F,P	OS N	G P	C, P, A	Com	1, 2, 3
13	Climate Emergency Design Guide	[32]	NfP	WorldGBC, UKGBC, Globa renewable generation forecast, National Grid's	V	M	E	O, E	B	Net zero whole life carbon for new and existing buildings	incremental by 2025, 2030 and 2050P,G	OS R	L (UK) P	A	Resi, Com, Edu	1, 2, 3

(*continued on next page*)

Table 2 (*continued*)

ID	Name	Reference	Organisation	Alignment with initiatives and frameworks	Disclosure type	Assessment method	Performance output	Lifecycle stage	Data coverage	Performance target	Pathway timeframe & type	Availability &Interface	Coverage &Sector	Scale	Building type	Scope
				Community Renewables Future Energy Scenario												
14	Investor Climate Action Plans	[28]	NfP	TCFD, TNFD, ISSB, NZIF, NZAOA, TSP, SBTi	V	M	E, C, M	NA	B, P	Net zero emissions	by 2050F	OS N	G C	P, A	NA	1, 2, 3
15	Net Zero Company Benchmark	[11]	NfP	TCFD, CDP, SASB, GRI, IGCC Asia, Ceres, IGCC, IIGCC, PRI, IEA NZE, SDA, TPI Carbon performance method	M	BU	E, C, M	NA	NA	IEA future scenario targets, net zero carbon emissions	by 2050F	OS N	L (Asia) C	C	NA	1, 2, 3
16	Net Zero Investment Framework	[39]	NfP	TCFD, EU Taxonomy, SDA, IPCC	M	M	E, C, M	NA	NA	Net zero	by 2050F	OS N	G C,P,I	P, A	NA	1, 2, 3
17	The Net Zero Asset Managers Commitment	[37]	NfP	TCFD, UN Race to Zero, NZIF, SBTi, NZAOA, TSP	M	TD	E, C, M	NA	NA	Net zero	NAC	OS N	G G	P, A	NA	1, 2, 3
18	2030 Challenge and Zero Tool	[3]	NfP	AIA, CBECS	V	M	E	NA	NA	Carbon reduction for new and existing buildings	Incremental by 2020, 2025, and 2030 T,P	OS N	G P	P, A	Resi, Com	1, 2, 3
19	ClimateWise Transition Risk Framework	[50]	A	TCFD	M	BU	C	NA	NA	NA	NAF	OS N	G I	C	NA	1, 2
20	Race to Net Zero Climate Emergency	[40]	A	WorldGBC, Australian Government, DGBC and UKGBC Paris Proof Method	V	M	E, C	O, E	B	Net zero whole life carbon for new and existing buildings	incremental by 2030, 2040 and 2050P,G	OS R	L (AUS) P	A	All	1, 2

$GtCO_{2e}$ or 91 $GtCO_2$) and the building sector (19.49%). As a result, it provides energy and carbon intensity not to exceed targets for different building types across the world.

CRREM involves a tool that benchmarks individual buildings' energy and carbon performance against what is called the CRREM pathways to track sectoral and country-level decarbonisation ambitions [12]. This study CRREM‘s climate risk assessment process includes collecting energy consumption, generation and occupancy data to determine the alignment between the asset performance and decarbonisation pathways. This is a bottom-up process involving mapping an asset‘s carbon and energy intensity against the decarbonisation pathways between 2020 and 2050 [12].

CRREM adopts a global, sectoral and country-specific downscaling method to develop decarbonisation pathways by allocating a fair share of the anthropogenic carbon budget to the property sector in numerous countries [46,23]. CRREM addresses operational emissions and uses a spreadsheet editor-based tool (Microsoft Excel) to benchmark a property‘s climate risk performance against the pathways to map the alignment by limiting the global temperature increase to 1.5°C by 2050 [27].

CRREM has developed country-specific pathways for Australia based on climate zones where some of the major and most populated Australian cities are located [13]. The CRREM method for Australia will benefit from further work by assessing and benchmarking Australian properties against the CRREM pathways. This further work will improve the granularity and application of the method, as well as monitor the current carbon emission reduction ambitions of the Australian building sector.

3.2. Selection of case study

Office buildings in Australia constitutes 25% of energy consumption within commercial buildings [14], Given that offices make up 49% of the Australian building stock and, they play a significant role in reducing emissions [14].

First, the whole building energy consumption data from commercial office case studies across Australia using the public energy register database of NABERS [36]. This is because CRREM pathways are determined for whole building energy consumption including base and tenancy [12]. NABERS assesses and benchmarks a building‘s performance with a rating ranging between 0–6 stars. NABERS energy performance rating is based on the actual energy consumption of a building, collected from the electricity meter and verified by an accredited assessor. Buildings with a current NABERS rating are found in the rating register available in the public domain [36]. Of the 3940 buildings in the NABERS Rating Register, 3460 were commercial offices and 2033 of those had an active energy rating. 455 buildings had whole building-related data on their energy use. A total of 431 NABERS-rated commercial office buildings across Australia were selected. They were selected based on the criteria, mainly due to being located in a climate zone with CRREM pathways and having whole building-related energy consumption data. Of the total 431 offices, most are in urban areas (which include the Central Business Districts-CBDs) and the rest are located in regional areas and in climate zones 1, 2, 3, 5, 6 and 7 are assessed as case studies to provide sufficient data for tracking sectoral decarbonisation measures against climate risk pathways [4]. The case studies are selected based on the criteria, mainly due to being located in a climate zone with CRREM pathways and having whole building-related energy consumption data.

Step 1	Access the Rating Register from the public database of NABERS-rated buildings across Australia (n = 3940 buildings)
Step 2	Select NABERS-rated commercial office buildings across Australia (n = 3460)
Step 3	Select NABERS-rated commercial office buildings with an active energy rating across Australia (n = 2033)
Step 4	Select commercial office buildings with whole building related data as CRREM requires both tenancy and base building (n = 455)
Step 5	Select commercial office buildings with whole building related data that are in climate zones 1, 2, 3, 5, 6 and 7 (n = 431 buildings)

The case studies are clustered based on their states and locations (e.g., urban regional, CBD-Central Business District); climate zones of those locations as per the National Construction Code (NCC) of Australia and the Koppen-Geiger climate classification; NABERS energy rating; and the average energy consumption per state and nationally (in kWh/m^2/year) (Table 3).

The average EUI of all buildings is 75.26 kWh/m^2/year. Buildings in Australia Capital Territory (ACT) are the highest in terms of their average EUI and they are all in climate zone 7. On the other hand, buildings in Tasmania are also in the same climate zone but their average EUI is much closer to the national average. New South Wales (NSW) is where most of the offices with a whole-building NABERS energy rating are located with a star rating ranging from 0 to 6. Buildings with the highest star rating range (3–5.5) are in South Australia (SA) with the lowest average EUI of 55.19 kWh/m^2/year.

3.3. Building carbon risk assessment of the selected case study

The following process of data curation for the climate risk assessment undertaken in this study is presented in Fig. 3. Data for the 431 buildings were downloaded from the Register and the final whole building energy consumption were converted into kWh/m^2/year to correspond with CRREM pathways. The whole building energy consumption was then normalised by the hours of operation, occupancy rate and floor area definition to ensure that the final energy consumption figure was comparable. This is because NABERS and CRREM use different floor area definitions, as well as NABERS factors in the hours of operation and occupancy rate while CRREM does not [12–13,36].

The energy consumption of the selected 431 buildings was analysed to determine whether it falls below or above the decarbonisation pathways, indicating their climate resilience. CRREM sets decarbonisation pathways for carbon emissions and energy consumption on a yearly basis between 2020 and 2050 for commercial office buildings, among other building types. These pathways are set separately for the various types of buildings within the scope of the CRREM method [13]. The pathways suggest achieving net zero carbon emissions by 2050 and reduced Energy Use Intensity based on a fair share of the carbon budget to limit global warming to 1.5 °C [12].

Step 1-5	The election process of the commercial office buildings with whole building related data in climate zones 1, 2, 3, 5, 6 and 7 (n=431 buildings) (explained in Section 3.2)
Step 6	Extract and convert the energy consumption in MJ/m^2 into kWh/m^2 to correspond with CRREM‘s pathways Calculate the total whole building energy consumption as: $\sum \boldsymbol{total}(\boldsymbol{E_{pr}} + \boldsymbol{E_{co}} + \boldsymbol{E_{ge}} + \boldsymbol{E_{dh}} + \boldsymbol{E_{dc}})$ Where; $\boldsymbol{E_{pr}}$ is energy consumed by procured electricity $\boldsymbol{E_{co}}$ is energy consumed by fuel consumption $\boldsymbol{E_{ge}}$ is energy consumed by renewable energy generated and consumed on-site $\boldsymbol{E_{dh}}$ is energy consumed by district heating $\boldsymbol{E_{dc}}$ is energy consumed by district cooling
Step 7	Normalise the total whole building energy consumption by the hours of operation, occupancy rate and floor area definition: $\sum \boldsymbol{normalisedE_{total}} * \frac{1}{\boldsymbol{hours_{op}}} * \frac{1}{\boldsymbol{rate_{oc}}} * (\frac{\boldsymbol{GIA}}{\boldsymbol{NLA}})$ Where; $\boldsymbol{hours_{op}}$ is hours of operation $\boldsymbol{rate_{oc}}$ is occupancy rate according to the Occupancy Patterns as per the National Construction Code $\frac{\boldsymbol{GIA}}{\boldsymbol{NLA}}$ is the floor area definition conversion (from NLA to GIA) according to the Property Council of Australia
Step 8	Climate risk assessment of the selected office building in accordance with decarbonisation pathways for Australia set by CRREM tool

Fig. 4 provides the CRREM decarbonisation pathways for carbon emissions (in $kgCO_2/m^2$/year) and EUI (in kWh/m^2/year) for selected offices in various climate zones in Australia. Both pathways present a decreasing trend from 2020 to 2050. The EUI pathway is somewhat

Table 3

List of office buildings clustered based on their location across Australia.

State	Number of buildings per location				Climate zones			NABERS Energy Rating range^	Average on-site energy consumption (kWh/m²/year)	On-site energy consumption range (kWh/m²/year)
	Urban*	Regional	CBD	Total	NCC	Koppen-Geiger	ASHRAE 169			
ACT	18	0	5	18	7	Cfb	3A	1.5–5.5	100.57	42–388
NSW	84	54	14	138	2, 5, 6, 7	Cfa, Cfb	3A	0–6	85.47	32–1626
VIC	83	14	9	97	6	Cfb	3A	0–6	80.56	26–446
QLD	62	33	8	95	1, 2, 3, 5	Aw, Am	2A, 1A	0–6	64.24	29–188
SA	18	1	6	19	5	Csa	3B	3–5.5	55.19	28–113
WA	45	9	8	54	1, 5	Csa	3B	0–5.5	61.79	28–313
TAS	6	1	6	7	7	Cfb	3A	2.5–5	74.03	42–98
NT	0	3	2	3	1	Aw	1A	3–5	70.62	70–93
Australia	316	115	58	431	1, 2, 3, 5, 6, 7	All above	1A, 2A, 3A, 3B	0–6	75.26	28–1626

*Urban areas include the CBD.

^The NABERS Energy Rating ranges from 0 to 6 stars with 0 stars (no star rating) being not rated, 1 star being "poor", 2 stars being "below average", 3 stars being "average", 4 stars being "good", 5 stars being "excellent" and 6 stars being "market leading".

Step 1-5 The election process of the commercial office buildings with whole building related data in climate zones 1, 2, 3, 5, 6 and 7 (n=431 buildings) (explained in Section 3.2)

Step 6 Extract and convert the energy consumption in MJ/m² into kWh/m² to correspond with CRREM`s pathways

Calculate the total whole building energy consumption as:

$$\sum \boldsymbol{total}\,(\boldsymbol{E_{pr}} + \boldsymbol{E_{co}} + \boldsymbol{E_{ge}} + \boldsymbol{E_{dh}} + \boldsymbol{E_{dc}})$$

Where; $\boldsymbol{E_{pr}}$ is energy consumed by procured electricity

$\boldsymbol{E_{co}}$ is energy consumed by fuel consumption

$\boldsymbol{E_{ge}}$ is energy consumed by renewable energy generated and consumed on-site

$\boldsymbol{E_{dh}}$ is energy consumed by district heating

$\boldsymbol{E_{dc}}$ is energy consumed by district cooling

Step 7 Normalise the total whole building energy consumption by the hours of operation, occupancy rate and floor area definition:

$$\sum \boldsymbol{normalised}\ \boldsymbol{E_{total}} * \frac{\boldsymbol{1}}{\boldsymbol{hours_{op}}} * \frac{\boldsymbol{1}}{\boldsymbol{rate_{oc}}} * \left(\frac{\boldsymbol{GIA}}{\boldsymbol{NLA}}\right)$$

Where; $\boldsymbol{hours_{op}}$ is hours of operation

$\boldsymbol{rate_{oc}}$ is occupancy rate according to the Occupancy Patterns as per the National Construction Code

$\frac{\boldsymbol{GIA}}{\boldsymbol{NLA}}$ is the floor area definition conversion (from NLA to GIA) according to the Property Council of Australia

Step 8 Climate risk assessment of the selected office building in accordance with decarbonisation pathways for Australia set by CRREM tool

Fig. 3. The methodology of climate risk assessment of selected NABERS-rated offices in Australia.

constant from 2037 to 39 onwards until 2050 due to the projections on global renewable energy generation [25]. The values plotted in the pathways for each year in various climate zones set the maximum performance threshold that is not to be exceeded. For instance, the not-to-exceed carbon emission target for 2050 is 0.6 $kgCO_2/m^2$/yearregardless of climate zone. This can be considered as a nearly zero emissions target and for this achievement, renewable energy generation is deducted from the actual energy consumption [12,23] . The highest 2050 EUI target is 75 kWh/m^2/yearand the lowest is 55 kWh/m^2/yearin climate zones 7 (e.g., Hobart) and 5 (e.g., Sydney), respectively. This indicates that a higher threshold is allowed by colder climates with increased heating demand, which aligns with the science-based methodology behind CRREM [13]. Further analysis of the 431 offices buildings across these locations and jurisdictions against the climate risk pathways are provided in Section 4 of this paper.

4. Results: Climate risk assessment of commercial office buildings

The energy performance of a total of 431 commercial office building

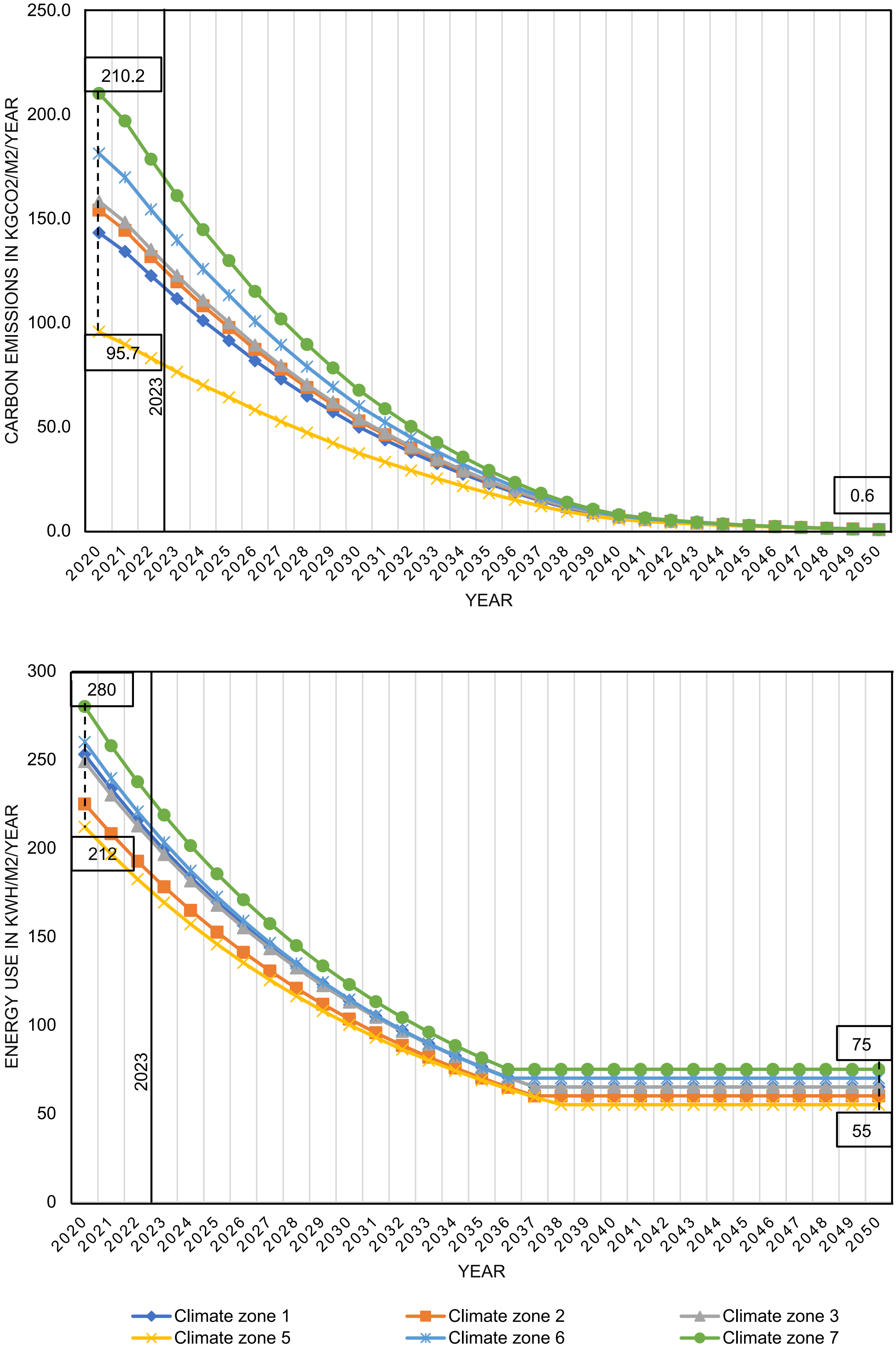

Fig. 4. CRREM decarbonisation (at the top) and on-site energy reduction (at the bottom) pathways and targets for selected commercial office buildings in Australia to limit global warming to 1.5 °C [12–13].

case studies has been assessed against the CRREM energy pathways. The findings are presented categorically and statistically, focusing on the sectorial energy performance gap (in Section 4.1), location-based (in Section 4.2) and climate-based climate risk assessment results (in Section 4.3), and performance benchmarking against energy ratings (in Section 4.4). The findings are discussed based on the decarbonisation ambitions of the commercial office sector, state and city-level climate transition plans and pledges, climate characteristics that influence building energy performance limits and trajectories, and the performance correlation between climate change risk and energy star ratings.

4.1. *The sectoral energy performance gap*

The analysed buildings are clustered according to their location, with respect to being in the CBD, urban or regional areas (Fig. 5) [7,41]. This section investigates the spatial distribution of certified buildings across urban areas in various states, shedding light on the dynamics of urban development and the role of CBDs within these contexts. Contrary to conventional expectations, the CBD represents a relatively modest fraction of the rated buildings across the majority of states. However, a notable exception to this trend is observed in Tasmania, where nearly all buildings, with the exception of one, are concentrated within the CBD. This unique pattern can be attributed to Tasmania's distinct state context, characterized by smaller cities in comparison to other states. Notably, Tasmania's capital, Hobart, stands out as one of the smallest and least densely populated capital cities in Australia, contrasting starkly with the metropolitan giants of Sydney, Melbourne, and Brisbane. Furthermore, our analysis highlights a clear correlation between the number of certified buildings and the general trend of urban densification, with Sydney, Melbourne, and Brisbane leading the chart in terms of building certifications within their respective urban areas.

It is generally a reasonable assumption that CBDs of cities serve as the primary hubs for top-tier commercial developments. Conversely, mid-tier office spaces tend to be more prevalent in both urban and regional areas. This observation underscores the distinctive characteristics and functions of these two types of commercial real estate locations, but also may explain the different capital investment across the two.

When assessing energy consumption, we can categorise excess energy usage as any amount exceeding the predefined thresholds. Comparing this excess energy with the maximum potential savings as calculated by the CRREM tool, the disparity between the two values reveals the remaining energy savings required to avoid stranding. This discrepancy also directly reflects the investment necessary for retrofitting buildings to meet carbon reduction targets. Hence, the difference between excess energy consumption and achievable savings, not only quantifies the energy gap but also the financial commitment needed to retrofit buildings and align them with the set carbon emissions objectives.

As depicted in Fig. 5, the current situation requires an investment that is more than twice the existing amount to bridge the gap. One potential limitation or factor contributing to the observed gap can be attributed to the manner in which CRREM handles energy retrofit calculations. Specifically, the tool does not account for potential offsets that may arise from solar photovoltaics (PV) installations. Instead, it assesses the net energy demand without distinguishing between energy sources. Over recent years, governments have significantly increased their investments in supporting building appliance upgrades and offering grants and feed-in tariffs for solar PV installations [53]. Unfortunately, these on-site solar PV contributions are calculated based on being added to the energy use of a building, rendering their beneficial effects to achieve a nearly or net zero energy performance invisible in the calculations. This is a limitation of the tool in terms of calculating energy balance; however, this limitation is due to the fact that the tool prioritises energy efficiency through demand reduction over energy balance [12]. Nonetheless, the gap in Fig. 6 and the trends depicted in the graph on the right clearly indicate the necessity to take action.

The majority of buildings stranding before 2037 in an almost linear crescendo. The steadily increasing curve of buildings nearing stranding underscores the critical need for immediate action. Retrofitting initiatives, such as energy-efficient upgrades and sustainability-focused enhancements, should be initiated in the next 7 years to prevent increasingly costly remediation actions and ensure a more resilient building stock across Australia.

Investment for retrofit in commercial assets encounters numerous intrinsic and extrinsic barriers in Australia [16][18]. First of all, the

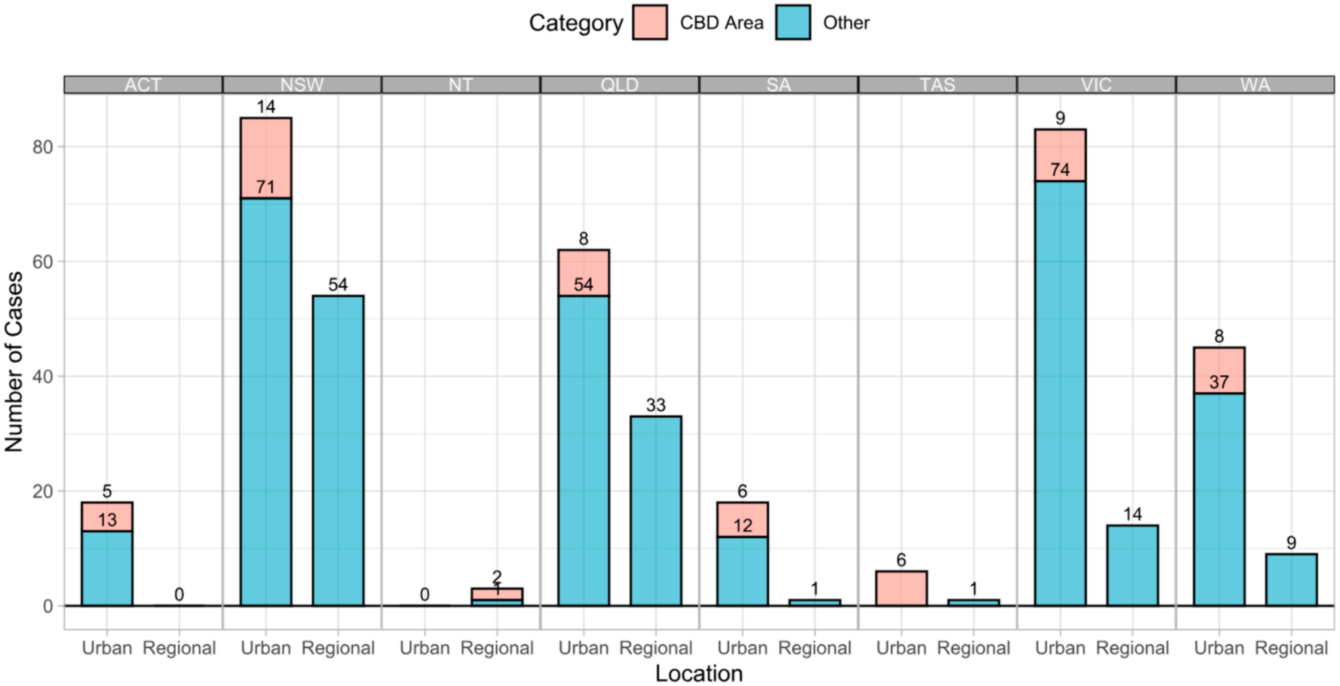

Fig. 5. Number of buildings (cases) assessed for climate risk based on locations, e.g., regional or urban areas (urban areas include the CBD) in different states.

nature of commercial buildings, especially large developments such as those usually found in CBDs and more at risk of stranding (Fig. 6). Large top-tier developments are characterised by complex dynamics and decision-making drivers, including internal competition for capital, organisational challenges and sustainability agenda. For example, a study demonstrates how corporations are usually more invested in sustainability drivers and discussions, while non-corporate organizations are driven by timing, including capital costs, asset management and reducing payback periods.

As carbon–neutral retrofits require effective collaborations between stakeholders and actors with oftentimes competing interests[42], top-tier offices are more likely to engage in the discourse, compared to mid-tier building owners [16]. However, both market segments shared challenges that hinder retrofit actions, such as the lack of sufficient upfront funding with a long return on investment compared to the potential immediate earns of the new build [1], which leads to a perceived short-term financial loss when retrofit is considered [15]. Further, intrinsic barriers to investment in retrofit are also magnified by a perceived absence of a problem to solve, a weak relationship to the core business, perceived hidden value of most upgrades, which are out of sight (e.g., HVAC) [62].

This mismatch in perceived value is further complicated by the landlord-tenant split, especially for mid-tier buildings. Building owners considering retrofitting tenanted buildings often hesitate to invest in energy efficiency or other environmental upgrades because they do not experience immediate benefits. An illustrative case is observed in Australian rental properties where enhancements that reduce energy, water, or gas expenses primarily benefit the tenants, yet the costs are borne by the landlords, who do not directly reap the financial rewards [31].

The large amount of energy performance gap is an aggregated value. This value is calculated as the whole sum of the excess energy use and energy savings of all 431 buildings. The formula for how this value is calculated is presented in Equations (1) and (2). In this context, excess energy refers to the on-site energy use value above the CRREM decarbonisation target to limit global warming to 1.5°C. Energy savings refer to the on-site energy use value below the CRREM decarbonisation target to limit global warming to 1.5°C. Buildings with "energy savings" are considered to be "climate-proof".

$$\sum \boldsymbol{aggregated\ E_{net}} = \sum \boldsymbol{aggregated\ E_{savings}} - \sum \boldsymbol{aggregated\ E_{excess}} \quad [kWh/m^2] \tag{1}$$

Where; $\boldsymbol{E_{net}}$ is the net on-site energy performance gap.
$\boldsymbol{E_{savings}}$ is the on-site energy savings.
$\boldsymbol{E_{excess}}$ is the excess on-site energy

$$E_{savings} = \sum savings\ (EUI_{building-1} - EUI_{CRREM\ decarb\ target}) + (EUI_{building-2} - EUI_{CRREM\ decarb\ target}) + \ldots [kWh/m^2] \tag{2}$$

Where; $\boldsymbol{EUI_{building-1}}$ is the energy use intensity of building-1.
$\boldsymbol{EUI_{CRREMdecarbtarget}}$ is the CRREM decarbonisation target applicable to building-1.

$\sum \boldsymbol{savings}$ and $\sum \boldsymbol{excess}$ are calculated using the same above formula. If the result is a positive (+) value, it is deemed $\sum \boldsymbol{excess}$; while if the result is a negaitve (−) value, it is deemed .$\sum \boldsymbol{savings}$

4.2. Location-based climate risk

As previously discussed, all buildings classified as at risk are projected to face stranding issues before the year 2040. The average stranding timeline across all states generally falls within the period of 2030 to 2035, with the exception of Western Australia (WA). Notably, when we focus on the states housing denser urban centres, e.g., NSW, Queensland (QLD), VIC, and ACT, the earliest anticipated stranding years range from 2020 to 2025. This implies that buildings in these regions have already begun to experience adverse effects due to the current climate conditions. Within this group of states, NSW exhibits a more evenly distributed stranding pattern, highlighting the pressing need for comprehensive building stock upgrades throughout the region. Conversely, in less densely populated states and territories, a concentrated peak in stranding incidents emerges after 2023. This provides an opportunity for government authorities to implement incentives and official measures aimed at encouraging timely interventions to address the impending challenges (Fig. 7).

From Fig. 8, NSW exhibits one of the highest percentages of stranding assets, with more than half of the cohort falling into this category. Similarly, WA has a higher rate of stranding assets with more than 60% of assets stranding. Whereas in the Northern Territory (NT),

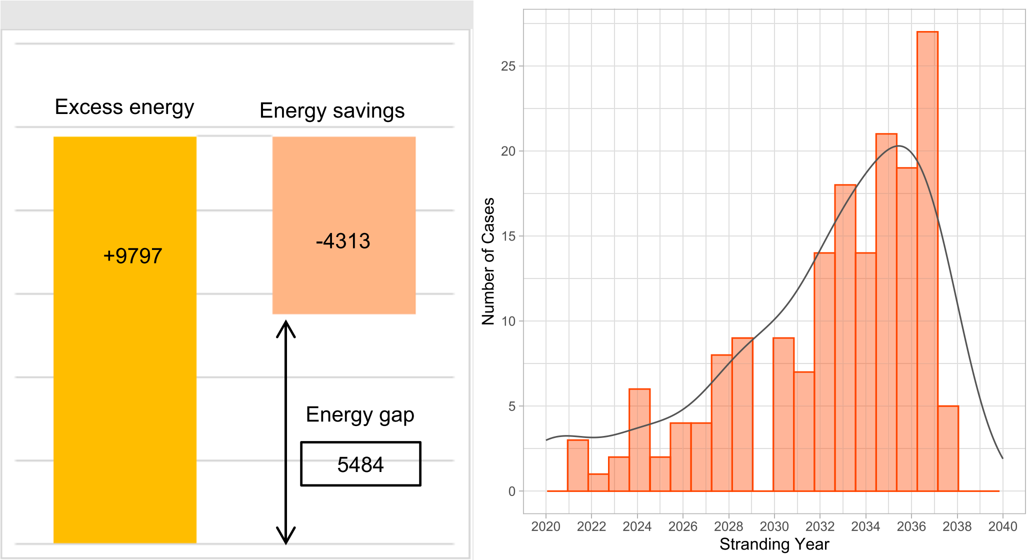

Fig. 6. (On the left) The aggregated on-site energy use intensity performance gap (in kWh/m^2/year) of NABERS-rated office buildings based on the difference between the excess energy consumed by buildings at risk and energy savings achieved by climate proof buildings. (On the right) The amount (count) of office buildings at climate risk based on their stranding year.

all assets (100%) are stranded; however, this is of lower significance since there are a total of three NABERS-rated office buildings in this state. This, in conjunction with the early onset of stranding, presents substantial challenges and expectations for the state to take proactive measures. Following NSW, the ACT ranks as the second highest, although the overall number of affected buildings is significantly lower.

In contrast, Victoria stands out with the lowest percentage of stranding assets. This favourable position may be attributed to recent initiatives for retrofitting and renovations, supported by both the State and Capital City governments. These efforts have likely contributed to a more resilient building stock in Victoria, reducing the proportion of buildings at risk compared to other regions.

An interesting trend can be observed when we compare assets in CBDs, urban areas, and regional locations. With the exception of NT, all other states predominantly experience stranding issues in their CBDs as opposed to regional areas.

4.3. *Climate-based climate risk*

Australia's climate zones, defined by the Building Codes Board of Australia (ABCB), exhibit significant variations in Heating Degree Days (HDDs) and Cooling Degree Days (CDDs) (https://www.abcb.gov.au/resources/climate-zone-map). The tropical zone (climate zone 1) experiences minimal HDDs due to its tropical climate, while CDDs is high because of persistent heat and humidity. In contrast, the subarctic zone (climate zone 6) has very high HDDs due to cold winters and low CDDs, indicating mild summers [38]. These extremes necessitate customized heating and cooling solutions, with a focus on cooling in zone 1 and efficient heating systems in zone 6. It's important to note that specific values may vary by location and year (Fig. 9).

Fig. 10 highlights substantial disparities in climate-resilient assets, stranding timelines, and asset distribution across various climate zones. A majority of the assets are in climate zones 5 and 6, accounting for 67 % of the total assets. Out of the 235 total assets, 107 are deemed climate-proof, while the remaining 128 (54.5 %) are projected to strand before 2031. Climate-proof performance refers to meeting, or not exceeding, the energy intensity targets of CRREM to limit the temperature increase 1.5°C temperature by 2050. As such, a 'climate-proof' building's energy use intensity in kWh/m^2/year below the CRREM pathway until 2050.

Notably, the most significant contrasts are observed between climate zones 1 and 6. In climate zone 1, known for its high CDDs, assets exhibit the lowest climate resilience, with 61.1% of assets expected to strand. Conversely, in climate zone 6, characterised by high HDDs and low CDDs, assets demonstrate the highest climate resilience, with 71.8 % classified as climate-proof. An underlying reason for this result may be that the CRREM method distributes a share of the carbon allocation in consideration of the HDDs and CDDS, mostly tolerating heating-dominated climates by providing those locations with a higher threshold for the energy use intensity [12].

Regarding stranding years, assets in climate zone 6, with the earliest stranding year of 2029, face a more immediate risk compared to those in climate zone 1, projected to strand by 2035. Furthermore, the analysis reveals significant geographic disparities in asset distribution. Given the substantial number of impending stranding cases, there is an urgent need to prioritize retrofitting and renovation efforts, especially in climate zones 5 and 6. Notably, the states of NSW and WA stand out as focal points when addressing the issue of stranding assets within these climate zones. To effectively mitigate these impending challenges, it is imperative to implement and enforce stringent regulations aimed at decarbonising these assets.

4.4. *Performance benchmarking against energy ratings*

Fig. 11 illustrates the performance of assets in relation to their NABERS energy ratings, highlighting a noticeable trend in the percentage of stranding assets and the average stranding year. The trend indicates a significant improvement in asset resilience as the energy rating increases from 4 to 5.5 stars. For instance, in the case of 4-star rated assets, 51% are expected to strand with an average stranding year of 2034. This figure declines to 38.2% for 4.5-star rated assets, stranding on average in 2035. The pattern continues with 5.5-star rated assets, where only 1.5% are expected to strand by 2038. However, the intriguing deviation from this pattern occurs with 6-star rated assets. Despite their higher energy rating, 79.9% of them are projected to strand with an average stranding year of 2031. The stranding assets are located in climate zone 5, urban areas of NSW and regional areas of QLD. The discrepancy might be attributed to various factors such as location-specific challenges, maintenance practices etc.

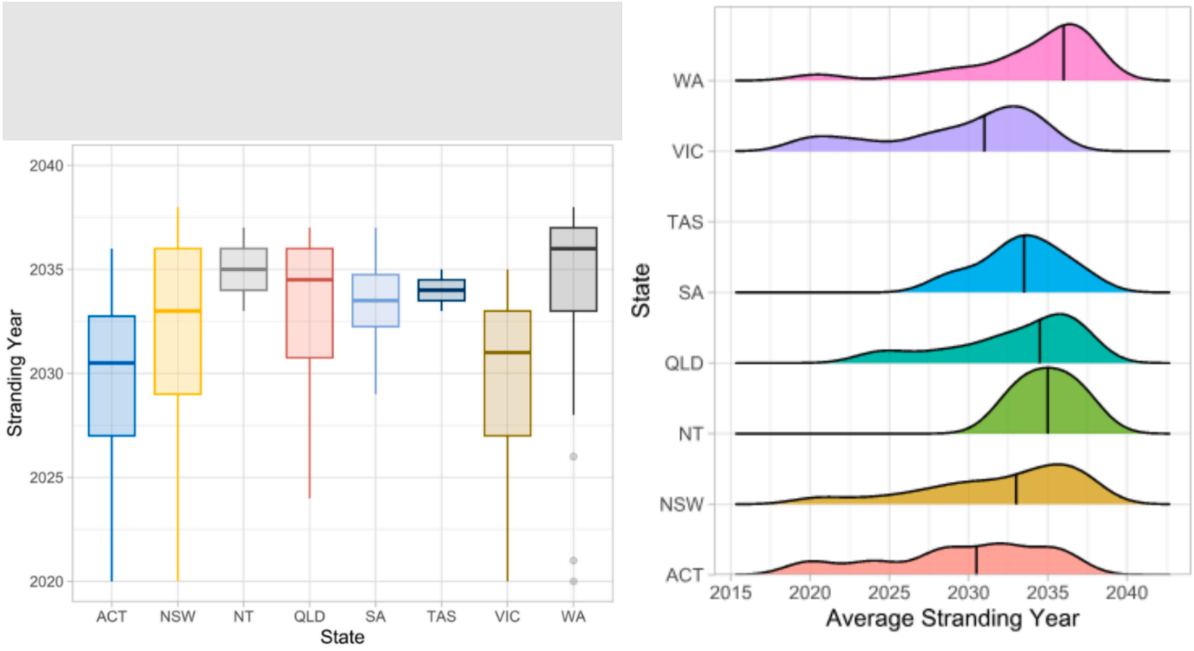

Fig. 7. The statistical analysis of office buildings at climate risk in different states based on their stranding year.

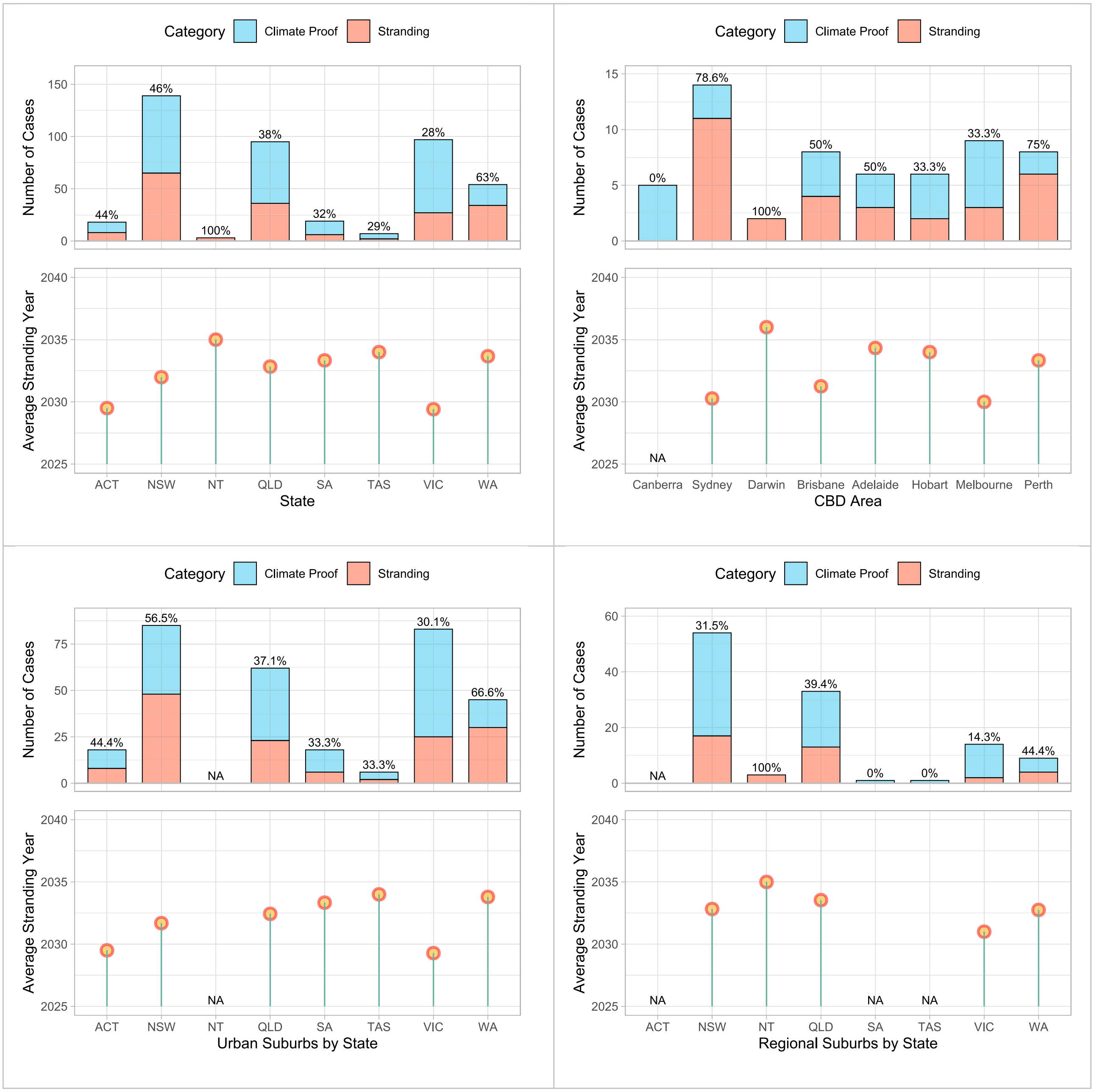

Fig. 8. The bar graphs at the top show the number of and proportion between the office buildings at risk and climate-proof offices. The line graphs at the bottom show the average stranding year of office buildings at risk based on location, including the suburb, city centre, urban and regional areas.

The reason why 6-star rated buildings have a high stranding risk is potentially due to the differences between the assessment methods behind the CRREM decarbonisation targets and the NABERS rating. CRREM targets are determined via a top-down approach, whereas NABERS adopts a bottom-up approach. Both approaches serve distinct purposes, and it is important to note that although a 6-star NABERS-rated building is deemed "market leading" in Australia, it may still not be meeting the global decarbonisation pathways. This is due to the methodological approaches behind the NABERS assessment and CRREM target setting. NABERS uses a bottom-up approach to determine and compare energy performance values across the sector, while CRREM uses a top-down approach to energy performance target setting by distributing a fair share of the remaining carbon budget based on limiting global warming to 1.5°C. For a successful and meaningful sectoral decarbonisation pathway, the bottom-up and top-down approaches that NABERS and CRREM use should be streamlined.

5. Discussion

A summary of main findings of the climate risk analyses of the commercial office buildings is given under Section 5.1. Recommendations to close the gap (Section 5.2) and limitations of the study (Section 5.3) introduced in the following sub-sections.

5.1. Discussion of main findings

The key takeaways of the climate risk assessment of 431 NABERS-rated offices across the country in different locations and jurisdictions are listed below:

a) Sectorial Energy Performance Gap and Retrofit Challenges:
- o The spatial distribution of certified buildings highlights the sectorial energy performance gap, necessitating retrofitting initiatives to

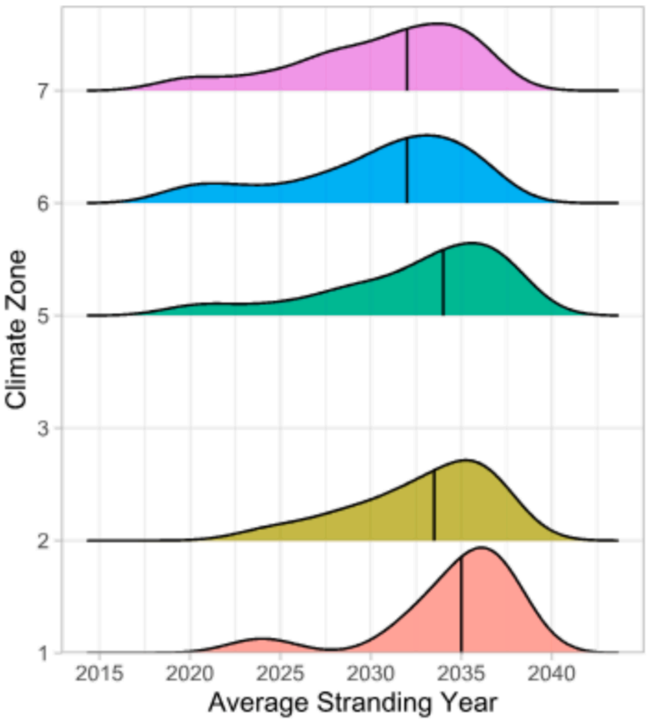

Fig. 9. Average stranding year of office buildings in different climate zones.

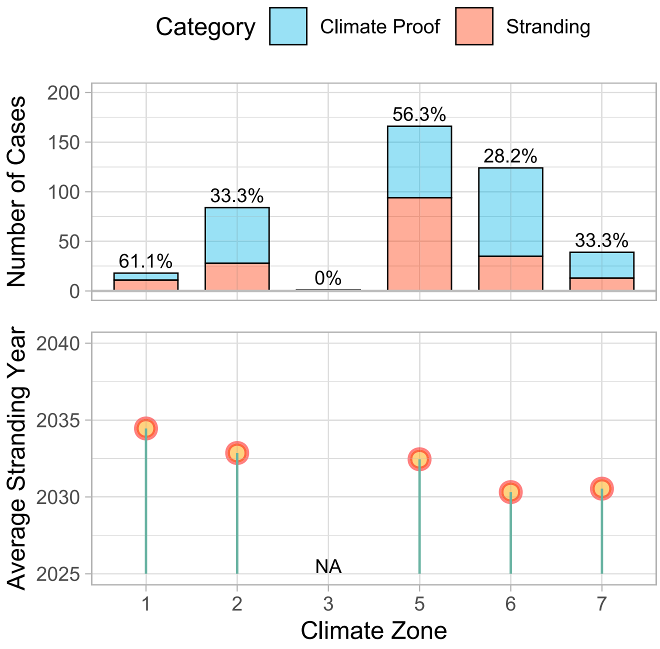

Fig. 10. The bar graphs at the top show the number and proportion between the office buildings at risk and climate-proof offices. The line graphs at the bottom show the average stranding year of office buildings at risk based on climate zone.

address energy consumption and achieve carbon–neutral design in commercial office buildings.

- Achieving carbon neutrality in these regions requires a holistic approach that considers the optimization of energy use and the integration of renewable energy sources, and passive design principles, while accounting for the sectorial energy performance gap.
- In addition, incorporating renewable energy sources (e.g., solar panels), implementing energy-efficient technologies, using sustainable materials, and adopting eco-friendly operational practices could be included.

b) Location-Based Challenges and Asset Concentration

- Location-based challenges in densely populated areas underscore the urgency of addressing energy and carbon–neutral buildings design, especially given the higher concentration of assets in these regions.
- architects and engineers must account for seasonal variations, maintain occupant comfort, and employ sustainable building materials and passive design principles while addressing these location-based challenges.
- Most CBDs have a modest fraction of rated buildings, except Tasmania where almost all buildings are concentrated in the CBD due to its unique state context. Sydney, Melbourne, and Brisbane lead in building certifications, correlating with urban densification trends. The higher concentration of assets in these areas further underscores the urgency and importance of addressing these challenges effectively.

c) Climate-Based Climate Risk Assessment and Asset Resilience:

- Climate-based climate risk assessment results are crucial for understanding asset resilience and guiding retrofitting efforts to reduce energy consumption and achieve carbon–neutral design across different climate zones.
- Customized heating/cooling solutions are necessary for different climate zones to enhance asset resilience and mitigate climate-related risks effectively.
- Climate zones with extreme HDDs and CDDs require specialized approaches for energy efficiency.

d) Performance Benchmarking Against Energy Ratings:

  - Performance benchmarking against energy ratings, such as NABERS ratings, provides insights into building resilience and stranding risks, emphasizing the need for continuous improvement and sustainable practices to achieve carbon neutrality.
  - While high-star energy rating buildings are designed to be more energy-efficient and environmentally friendly, achieving carbon neutrality requires benchmarking against energy ratings and adopting measures beyond the initial rating, considering factors such as building's design, construction, energy sources, operational practices, and global carbon reduction targets.
  - The analysis of building stranding highlights the urgency of retrofitting efforts, with denser urban centers facing earlier stranding issues. Assets in climate zones 1 and 6 demonstrate varying levels of climate resilience, indicating the need for tailored solutions in different geographic areas.

5.2. Recommendations to close the performance gap

Several variables impact the energy performance of buildings. Some of these include the actual energy consumption of the building, consumed fuel type (e.g., electricity, gas), total floor space and floor area definition (e.g., NLA, GIA, GFA), the occupancy rate and pattern (e.g., occupancy schedule), location and context (e.g., urban, regional, the surrounding environment, climate), building design and performance characteristics (e.g., mechanical systems, passive design, the building fabric, orientation, solar access). These variables impact the climate risk assessment of a building as well. In addition, climate risk assessment is influenced by the following factors, involving the completeness and availability of data (whole building data including tenancy and base buildings), the emission factors of different fuel types based on the location of the building, among others.

Acquiring complete data on the variables impacting the energy performance of buildings have a significant impact on closing the performance gap to decarbonise the operational emissions of commercial offices. Once sufficient actual data is acquired, implementing decarbonisation strategies to reduce the energy demand and offset it through

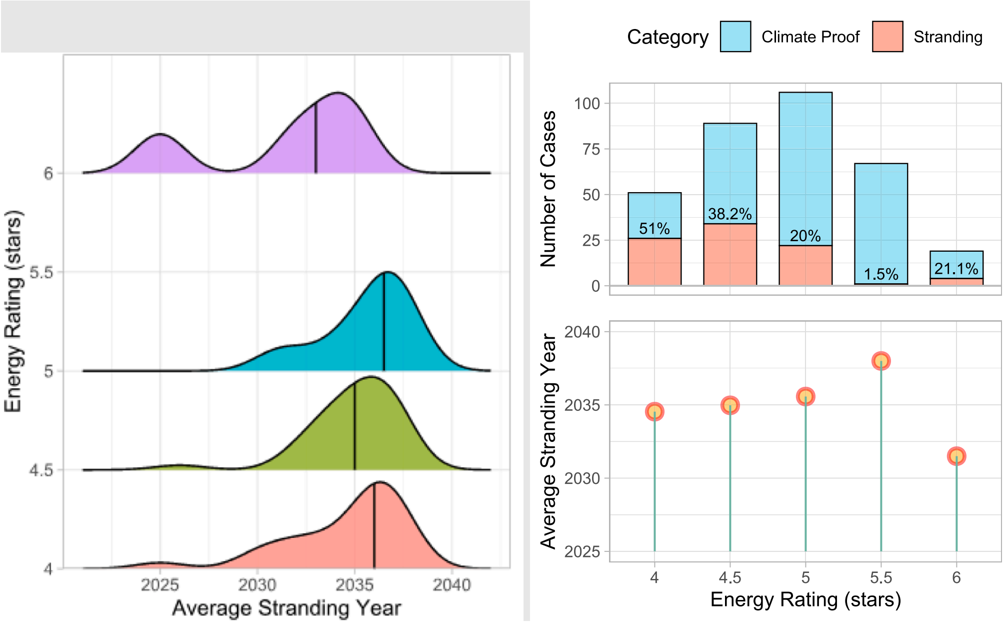

Fig. 11. (On the left) The average stranding year of buildings based on NABERS energy star rating. (On the right) The bar graphs at the top show the number and proportion between the office buildings at risk and climate-proof offices. The line graphs at the bottom show the average stranding year of office buildings at risk based on NABERS energy star rating.

verified renewable energy sources are recommended. Moreover, several major design, construction, management behavioural and operational aspects can help deliver decarbonised offices, including but not limited to the following, based on our analysis:

Retrofitting for energy demand reduction

- **Electrification of buildings:** Phasing out fossil fuel consumption in buildings by electrification will help reduce the energy use from fossil fuels transitioning to all electric operations for buildings. Depending on the gird energy mix of a country, electrification can mean net zero operating emissions. If a country‘s energy mix is not “clean” and involves fossil fuels, electrified buildings are ready to transition away from fossil fuels when the grid becomes “green”, as the consumption of gas, is already dealt with.
- **Passive design:** Designing, retrofitting and operating buildings based on the characteristics and needs of their location‘s climate through passive design solutions can help reduce the energy demand.

Asset management for decarbonisation

- **Asset lifecycle:** Investing in maintenance and energy-efficient upgrades can increase the lifecycle of an asset and decrease its energy demand, especially in consideration of the short and long-term climate change risks and trajectories.
- **Asset management for climate:** Developing an asset management and operation plan for decarbonisation to meet the local and global short and long-term climate benchmarks may help set out a meaningful and actionable pathway to meet these targets.

Occupant-owner collaboration

- **Occupant behaviour:** Educating and increasing the awareness of building occupants to make sustainable behavioural choices to contribute to the decarbonisation of the asset by reducing the operational energy may help the asset owners reach the climate targets.
- **Data collection and sharing:** A collaboration between occupants, property managers and asset owners for data collection and sharing on the energy consumption of the building can help acquire more complete information to address the decarbonisation aims.

Initiative for consistent and comparable climate targets

- **Climate targets cohesion:** A complete, consistent, cohesive and comparable study on how and to what extent local and global climate targets align with building sustainability benchmarks and ratings can help draw out the current state and future trajectory of decarbonising the building stock. If local ratings are matched against global climate pathways, policies and protocols, the achievement of these pathways can be further streamlined.

6. Limitations

The limitations of this study are twofold: (a) limitations of the CRREM tool used as an assessment method in the study, and (b) the limitations of using a building energy performance dataset available in the public domain without having access to extensive individual building data. Further details on these limitations are provided in the following paragraphs.

a. **Limitations of the CRREM tool:** The CRREM method has a distinct approach to considering the contributions of renewable energy generation to the overall performance of a building. As such, renewable energy generated from on-site sources are calculated based on being added to the energy use of a building, rendering their beneficial effects to achieve a nearly or net zero energy performance invisible in the calculations. This is a limitation of the tool in terms of calculating energy balance; however, this limitation is due to the fact that the tool prioritises energy efficiency through demand reduction over energy balance [12].
b. **Limitations of the building energy performance dataset:** The dataset used in this study is the NABERS Energy Register available in public domain [36]. This dataset has been used in order to compare the energy use intensity of the NABERS-rated commercial office buildings across Australia against the global and local CRREM decarbonisation pathways. The CRREM method is most applicable to

large datasets to enable tracking decarbonisation efforts to limiting global warming to what is agreed in the Paris Agreement. Although using the NABERS dataset provides the needed quantity and extent of building energy use intensities across the country, it poses limitations too. Limitations associated with using the NABERS dataset include the lack of undertaking multifaceted assessment of individual buildings and having further information on the characteristics of individual buildings limiting more in-depth investigations.

7. Conclusions

This study aimed at evaluating the climate risk of commercial office buildings in Australia to determine the global alignment with CRREM pathways and retrofit actions required. To do so, first, 20 climate risk assessment tools for buildings were reviewed and analysed in order to find the most suitable tool for the study. Criteria to find the tool included having global and local decarbonisation pathways, providing targets for limiting temperature increase to 1.5°C by 2050 as per the Paris Agreement to address the global efforts and setting science-based energy use intensity targets for commercial office buildings. Findings suggested that the CRREM tool had these properties and, therefore, had been used in this study. As such, CRREM was the only tool available with decarbonisation and energy targets for Australia and the globe. Then, a total of 3940 buildings registered in the NABERS Rating Register were scanned, among them 3460 commercial offices were detected. 2033 offices had an active energy rating, and 455 had complete whole building-related data on their energy use. From this pool, 431 NABERS-rated commercial office buildings across Australia were specifically selected based on criteria that primarily included being located in a climate zone with CRREM pathways and having comprehensive whole building-related energy consumption data. Using the CRREM method, the energy use intensities of these buildings were benchmarked against the decarbonisation pathways. The results were compared based on climate zones, jurisdictions, locations and NABERS energy ratings. It was found that 58.24 % ($n = 251$) of the buildings are climate-proof, meaning that they meet the 1.5°C pathways by having an operational energy use intensity below the decarbonisation target. An energy use intensity of 5484 kWh/m^2/year in total remained as an aggregated net performance gap. Most energy-efficient offices were found in the state of VIC, within the CBD of Melbourne. Most improvement was needed in the NT at the capital city of Darwin. To close the performance gap, measures that could be taken in asset management, occupant-owner collaboration, retrofitting and maintenance of offices for increased energy efficiency were provided as recommendations. Future works could focus on identifying case-specific strategies and applying the recommended measures to calculate the improvements on the individual building‘s performance.

CRediT authorship contribution statement

Aysu Kuru: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Kun Lyu:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ozgur Gocer:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Arianna Brambilla:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Deo Prasad:** Writing – review & editing.

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.

Data availability

Data will be made available on request.

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