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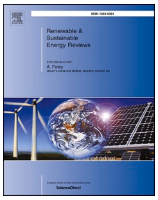

Resilience of the higher education sector to future climates: A systematic review of predicted building energy performance and modelling approaches

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ABSTRACT

A continued upward trend in global greenhouse gas emissions is estimated to see average temperatures rise by 2.7 °C before 2100. This warming effect presents risks to global infrastructure and built assets that should be identified to minimise negative consequences on inhabitants. For higher education estates, a key challenge is to maintain high indoor environmental quality standards whilst mitigating increased cooling loads under future climates. Findings from this meta-analysis suggest that existing passive cooling mechanisms may be insufficient to tolerate predicted increases in summertime temperatures, even in cooler UK climates. Across typologies, peak electricity demand for mechanically cooled higher education buildings was estimated to increase the most for halls of residences (4–27 %) and the least for laboratory buildings (0–5%) by 2080. Under a high emission scenario, the increase in total annual energy consumption by 2050 varies widely across studies (+5–33 %), although almost all cases predict a greater increase in cooling energy consumption than decrease in heating energy consumption. Probabilistic climate projections are the predominant source of uncertainty for predictions of energy demand, with the difference between low and high emission scenarios contributing to 34–44 % of variability in predicted annual cooling energy consumption in 2050. Further research is warranted to identify the most likely indicators of future building performance across a range of university building typologies. This work provides recommendations on expanding the evidence basis through development of standardised climate change impact assessments.

1. Introduction

Under current policies, a continued upward trend in greenhouse gas (GHG) emissions is estimated to cause global temperatures to rise by 2.7 °C above 1850–1900 levels before the end of the century [1]. Since the spatial distribution of warming is non-uniform, a 2.7 °C rise in global mean surface temperature is associated with substantially higher temperature increases in many land regions, with the urban heat island effect further exacerbating the warming impact experienced in large cities [2]. This warming effect and associated extreme climate events will continue for several centuries following the stabilisation of atmospheric CO_2 [3]. Identifying the risks and opportunities that climate change presents to infrastructure and built assets can help to inform the development of policies, allocation of resources, and macroscale planning of adaptation pathways, thus minimising the potential wide-spread future impacts of global warming.

The consequences of climate change on the built environment are extensive and reach across multiple fields of research [4,5]. On the subject of thermal performance, buildings can amplify or suppress the effects of global warming, thus a small change in external temperature can have a significant impact on future operation [6]. For example, higher global temperatures result in shifts in building energy use patterns from heating to cooling [7,8], particularly in the heating-dominant regions of the Northern hemisphere [9]. Rising minimum and maximum temperatures risk HVAC capacity mismatch, whereby some systems operate inefficiently at part-load due to a lower heating peak demand or are unable to handle increased cooling peak load requirements. In the UK, until the recent implementation of Part O [10,11], there was no regulatory requirement for overheating analysis. Therefore, a significant increase in external temperatures may also cause shifts in thermal operating conditions, particularly as the bulk of the increase in mean

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Abbreviations

A/V	area to volume ratio
CO_2	carbon dioxide
DSY	design summer year
EUI	energy use intensity
GFA	gross floor area
GHG	greenhouse gas
HE	higher education
HVAC	heating, ventilation and air conditioning
$kgCO_{2e}$	kilograms carbon dioxide equivalent
kWh	kilowatt hour
nZEB	near zero-energy building
PRISMA	preferred reporting items for systematic reviews and meta-analyses
ProCliPs	probabilistic climate profiles
PV	photovoltaic
Rel.diff	relative difference
SHGC	solar heat gain coefficient
SSCF	site-to-source conversion factor
TMY	typical meteorological year
USD	United States Dollar
VT	visible transmission
WWR	window-wall ratio
ZEB	zero-energy building

annual temperature is expected during summer months [4].

Resilience refers to the capacity of built assets to endure acute shocks and chronic stresses while successfully adapting to long term change [12]. In relation to climate change, resilient buildings must withstand the increasing frequency and magnitude of hot spells and higher summertime mean temperatures [2]. Impact assessments can be used to quantify this aspect of climate change resilience by measuring the extent of overheating [13], or in the case of mechanically cooled buildings, the extent to which weather-dependent energy loads are amplified under future climates [14]. Impact assessments can also be used to evaluate the efficacy of a range of interventions (i.e. climate change adaptation measures) in mitigating associated risks [13]. Climate change resilience is dependent on a multitude of factors, such as the building properties, occupancy patterns and key processes, many of which can be difficult to predict and likely to change, themselves, in moderating their contribution to climate change [4,8,15]. Detailed climate change impact assessments can improve understanding of factors effecting this relationship, particularly when characterising and differentiating between buildings within the same sector.

In 2012, de Wilde and Coley reviewed the emerging field of research on climate change impacts on the built environment [4], noting a strong focus on domestic buildings and offices, and suggesting that a wider range of building types and configurations, including universities, warranted further investigation. Several other motivations exist for researching climate change adaptation pathways within higher education (HE) estates. Substantial growth in the sector in the late 1950s and 1960s [16], when energy efficiency regulations were poor in comparison to present-day standards, incentivises the retrofit or refurbishment of much of the existing HE building stock. There are also strong drivers to improve the energy efficiency and reduce carbon emissions of HE buildings, with many universities having committed to carbon neutrality by 2050 or earlier [17]. In addition, HE institutions continue to invest heavily in their estates, driven by the high environmental standards needed to ensure continued student recruitment [16]. This provides the HE sector with opportunities to adapt to future climates.

This research responds to the lack of a consolidated body of evidence on the impacts of climate change on educational building typologies. HE buildings have distinct design features and characteristics, which have not yet been reviewed in the context of future building thermal and energy performance. In addition, there is an absence of public sector guidance on methodological approaches to conducting climate change impact assessments. In response, the questions addressed by this work are two-fold: (1) What does the current body of research indicate about the future preparedness of the HE building stock to climate change, with respect to overheating and energy consumption? (2) How is climate change impact being assessed within public sector building research? An overview of case studies identified from literature is provided, and specific design features reviewed with respect to their impact on future building performance. Modelling strategies and assumptions made relating to the changing state of the energy sector are subsequently reviewed. Recommendations are provided for a more standardised approach to climate change impact assessments within this sector.

2. Review methodology

This section presents the search strategy, inclusion/exclusion criteria, a quantitative analysis of the search results, and the key design criteria by which each article was reviewed. The systematic review process adopted was based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol. PRISMA offers the advantage of process transparency and replicability of results through an explicit database search strategy, and pre-defined eligibility criteria [18]. The adapted four-step review process is presented in Fig. 1: (1) defining key terms, (2) identifying relevant articles, (3) screening based on pre-defined eligibility criteria, and (4) a combined quantitative and descriptive analysis of included articles.

2.1. Search strategy and criteria

The systematic review protocol attempted to capture research relating to three conceptual themes identified in Fig. 1. Search terms conveyed the research focus on climate change resilience as defined by future thermal and energy performance. Whilst the initial search was conducted on HE buildings only, proxy search-terms were incorporated to draw on evidence from similar buildings under other economic activities: schools, workshops, laboratories and libraries. Results from proxy buildings supported quantitative energy analyses, whilst HE case studies were isolated for the review of factors relating to design, governance, investment and energy decisions that are unique to these typologies. The temporal scope included research published from 2000 to 2022, resulting in 673 unique articles. On applying the inclusion and exclusion criteria in Table 1, there was a steep decline in the study number. This reflected a tendency for studies to address climate impacts on building design under current climates only, despite frequent referencing to climate change.

2.2. Analysis of search results

Industry publications indicate a rising interest in the practical application of climate change impact and adaptation in the built environment [12], with evidence of climate change resilience being considered at the design stage of several real-world HE case studies [19]. Despite this, the evidence basis for the resilience of the educational building stock towards climate change has progressed only slightly in recent decades, demonstrated by the low albeit expanding article numbers in Fig. 2; the predominant research focus has been on office buildings. In total 46 publications were identified, representing 39 unique case studies (HE: $n = 17$, proxy: $n = 22$). The majority of these (n

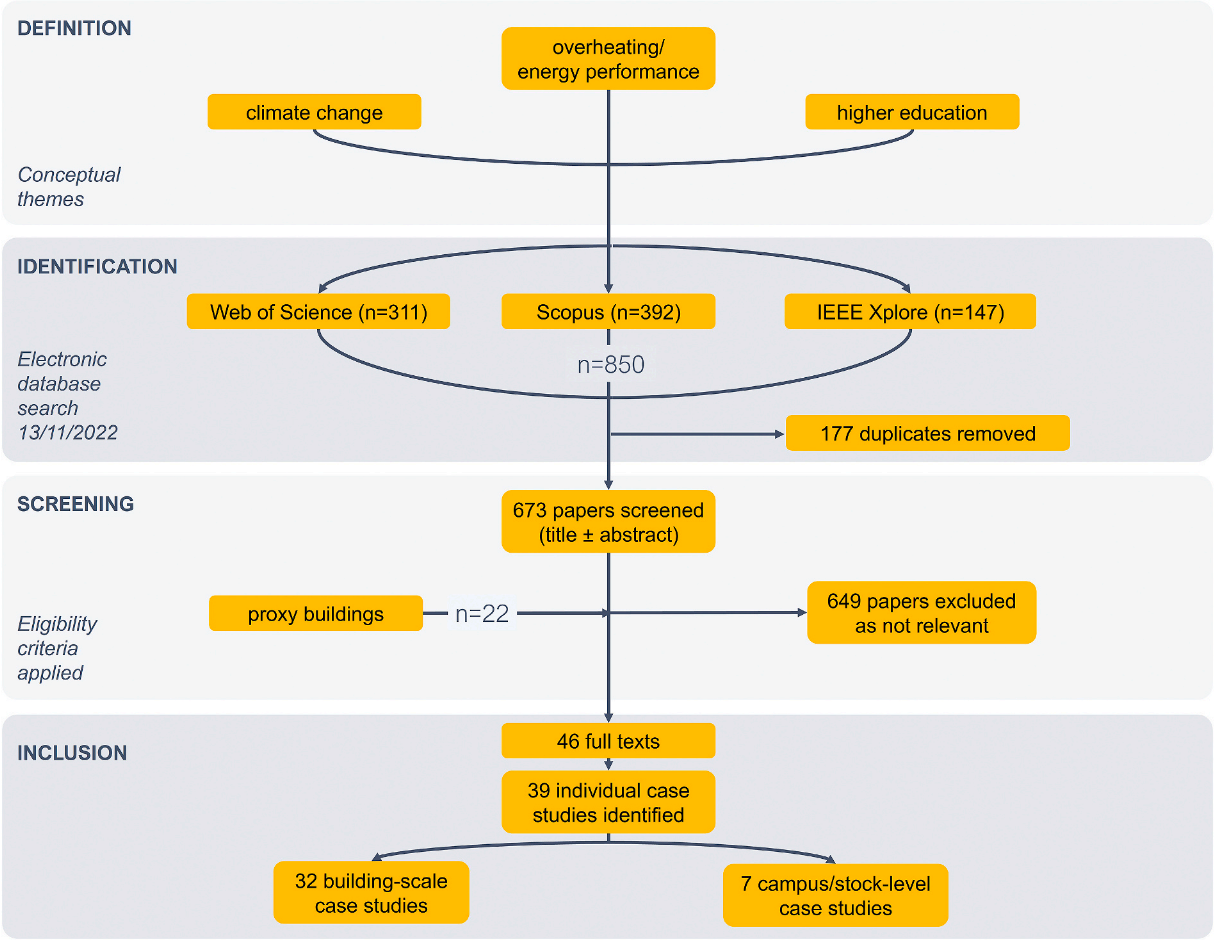

Fig. 1. PRISMA-adapted systematic review protocol.

= 32) were conducted at the individual building scale, whilst the remaining 7 case studies made observation at a campus or stock level. The geographical distribution of articles based on the location of case studies is depicted in Fig. 3. Despite the vulnerability of many areas in the Global South to the impacts of climate change, prior research focuses on HE and proxy case studies in northerly and western regions; in particular, the United Kingdom (n = 14; 30 %) and United States (n = 9; 20 %). In response to this disproportionality - and to learn from extreme heat management in hotter climate regions - an additional screening was conducted for HE buildings in climate-vulnerable Middle-Eastern, Southern and equatorial regions under current climate conditions.

2.3. *Performance indicators for further analysis*

The results from this review process are described in two sections. The first classifies the case studies according to typology and the key design characteristics. The design features shown in Table 2 were identified by the authors to be important indicators of future building performance for the reasons justified and were used as descriptors for the qualitative evaluation of case studies. The number of articles that attempt to evaluate each of these design attributes is also shown in Table 2; the majority focus on key concepts of 'retrofit', 'passive design' and 'scaled' building networks. The second section of this review categorises the performance metrics and modelling assumptions used in these articles, establishing the feasibility of cross-study comparisons. The studies predominantly utilise dynamic simulation modelling and involve a range of methodologies and objectives.

Table 1
Inclusion and exclusion criteria applied to filter articles.

Inclusion Critaria	Exclusion criteria
1.Includes case study relating to the HE built environment	1.Climate impact relate to mold, moisture,flooding,structural damage
2.contains a measure of climate change impact as reported outcome	2.On-campus residential houses
	3.On-campuse test modules
	4.Systematic review
	5.No full text

3. Findings

3.1. *Case study classification*

An overview of the final building-level case studies is presented in Table 3. The following section draws on evidence from these case studies to investigate the influence of specified design features on future building performance.

3.1.1. *Use function*

Higher education buildings are often characterised as having high and intermittent internal heat gains resulting from irregular occupancy densities [24]. These can be difficult to predict and considered a key source of uncertainty in the prediction of overheating and building energy consumption up to 2080 [8]. Primary building functions of reviewed HE and proxy buildings are presented in Table 3 in accordance with the CIBSE Energy Benchmarking Tool [25]. The literature adopts various modelling techniques to depict function and use patterns, according to the main purpose of the research; some studies aim to highlight segments of the HE building stock that are most susceptible to

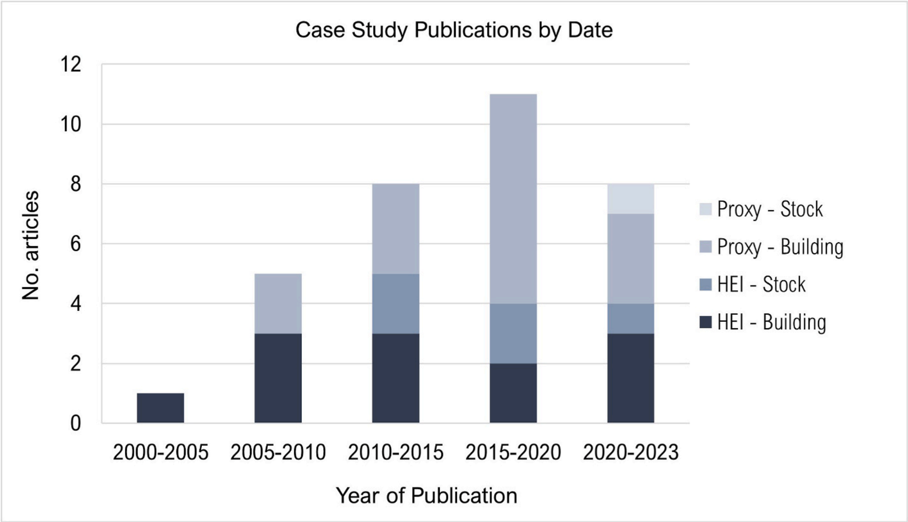

Fig. 2. Number of articles focusing on higher education and proxy systems as receptors for climate change impact studies.

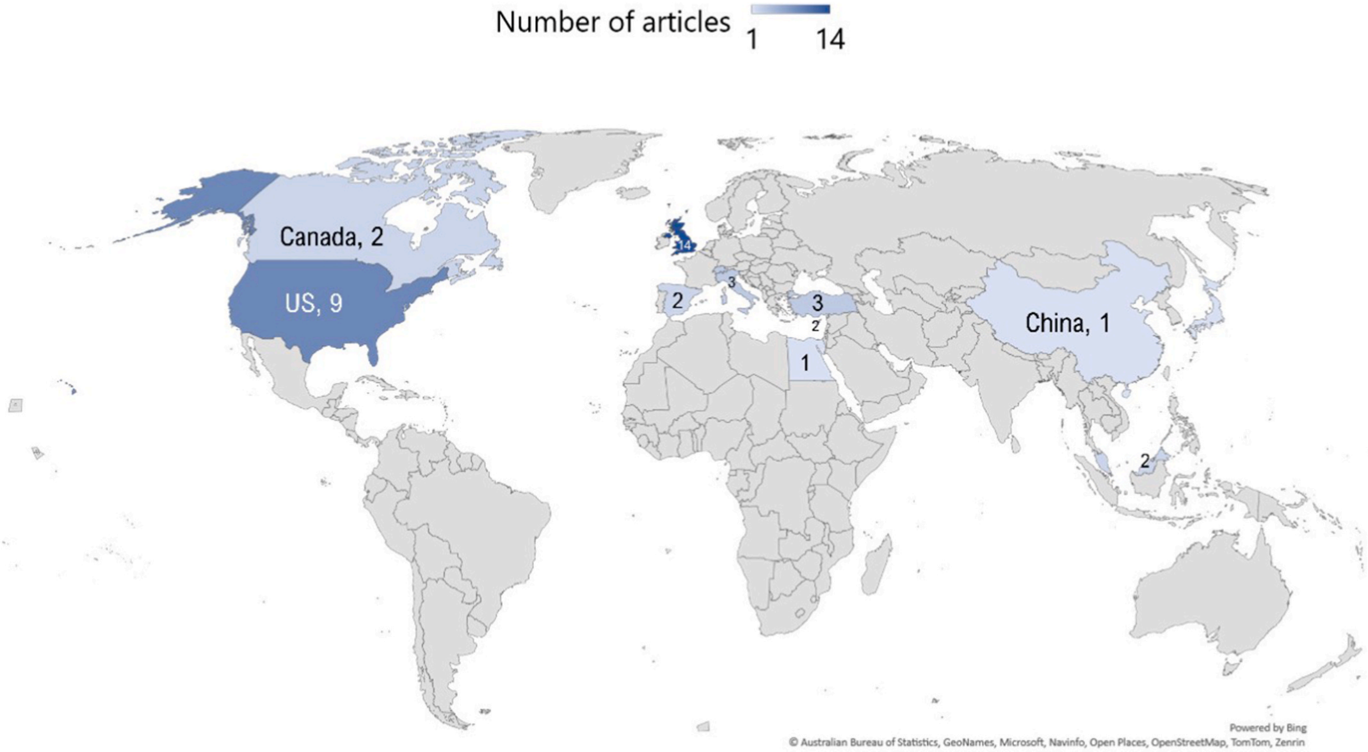

Fig. 3. Geographical distribution of articles based on case study location.

Table 2
Reviewed design characteristics and building properties; number of studies considering each design feature.

Design Feature	Relevance to future HE building performance	No. Studies
Use function	Typically a strong determinant of heat and electricity use; standard for benchmarking [20,21]..	3
Construction age and styles	Geometries and thermophysical properties of materials impact heat transfer and gains; age also acts as an indicator of energy efficiency and component deterioration [22].	3
Retrofitting	Usually targeted at reducing heating loads in cooler climate regions; can lead to an increase in cooling energy demand.	12
Passive design strategies	Shading can limit heat gains; advanced natural ventilation and optimised glazing design can reduce reliance on active HVAC [10].	15
Systems configuration	Typically a strong determinant of energy use; sometimes used for benchmarking [23].	9
Urban geometry and scale	Resilience pathways for HE campuses require planning of energy networks at scale; buildings' performances under a changing climate may be impacted by local microclimates and urban geometries.	13
Location	Global warming is non-uniform [2]; HE buildings in the global south are expected to experience larger increase in summertime temperature, but may be better equipped to handle extreme heat.	1

Table 3

Summary of building-level case study attributes, focusing on key factors considered to influence the climate change resilience of HE estates. Window-to-wall ratio (WWR) defined by low (approx. $\leq$30 %), med (approx. 50 %), high (approx. $\geq$70 %). Assumptions based on electricity demand profiles presented by Luo and Oyedele [39]. *Proxy buildings: CS13: Engineering workshop, CS14: Library.

Case Study (CS) No.	Location	CIBSE TM46 Use Function	Architectural Classification	Construction Year	Refurbishment/ Retrofit Year	No. Stories	Gross Floor Area (m2)	Envelope Properties	Fenestration	Cooling Design Strategy	Reference
1.	*Kuala Lumpur, Malaysia*	Library or learning centre	British Colonial	1959	-	*4*	*13,850*	High thermal mass	Low-med WWR Tinted windows	Mechanical ventilation	[40]
2.	*Sheffield, UK*	Academic - other	Postmodern	1993	-	*5*	*9031*	Brick outer leaf Large central courtyard Shadow-casting context	Low WWR Double and single glazed windows	Natural ventilation	[41]
3.	*Pennsylvania, US*	Academic - other	English classicism, 17th century style	1906	-	*4*	*13,000*	Brick outer leaf High thermal mass	Low WWR Cast stone frame windows	Mixed-mode Natural ventilation District cooling	[33]
4.	*Southampton, UK*	Academic - Engineering	International	1963	-	*10*	*4666*	Four identical façades Poor airtightness	Med WWR Single-glazed steel frame	Natural ventilation (single-sided)	[24]
5.	*Birmingham, UK*	Academic - other	Modern	1971	*2007*	*12*	*9216*	Concrete frame S-façade vertical brise-soleil Poor airtightness	High WWR Steel frame windows	Natural ventilation (single-sided)	[32]
6.	*Nagoya, Japan (simulated in various locations)*	Academic - Engineering	Contemporary	-	-	*10*	*15,980*	Brick outer layer	Single glazed aluminium framed windows	Mechanical cooling (air conditioning)	[9,42]
7.	*Sheffield, UK*	Academic - other	Postmodern	2004	-	*5*	*1850*	Free standing High thermal mass S-facing atrium and active façade	High WWR (entire N + S façade) Automated internal shading	Natural ventilation (cross-flow, stack) Night-time cooling	[30,41,43,44]
8.	*Plymouth, UK*	Academic - art and design	Contemporary	2007	-	*9*	*13,048*	Reinforced concrete frame Steel roof structure Copper cladding	High WWR (entire N&S façade) Double-glazed	Mechanical ventilation Air-cooled chillers	[34,45,46]
9.	*Valladolid, Spain*	Academic - biology/ medicine	Contemporary, ZEB	2013	-	*3*	*7500*	Reinforced concrete structure Autoshading Internal insulation High thermal mass $U = 0.17$ W/m^2.K Green roof ($U = 0.15$ W/m^2.K)	Double glazed argon-filled windows	Mixed-mode Natural ventilation w/ geothermal recovery Absorption cooling	[29]
10.	*Lausanne, Switzerland*	Academic - chemistry/ physics	Schwyz Vernacular	1982	*1990/1999*	*3*	-	High thermal mass Wall $U = 0.4$ W/m^2.K External shading Anidolic system Timber clad	Med WWR (S-façade) Wooden frame windows Double glazed IR coating	Natural ventilation	[28]
11.	*Bristol, UK*	Academic – other	Purpose built	1991	-	*3*	-	Brick outer leaf Spandrel panels	Low WWR Internal shading	Assumed natural ventilation*	[39]
12.	*Bristol, UK*	Academic – other	Postmodern	–	-	*5*	-	Brick outer leaf High form factor	Low WWR Venetian blinds	Assumed mixed-mode*	[39]

(*continued on next page*)

Table 3 (*continued*)

Case Study (CS) No.	Location	CIBSE TM46 Use Function	Architectural Classification	Construction Year	Refurbishment/ Retrofit Year	No. Stories	Gross Floor Area (m2)	Envelope Properties	Fenestration	Cooling Design Strategy	Reference
13.*	*Unknown, UK*	Academic - Engineering	Unknown	-	-	*1*	*1678*	Shallow plan design Portal frame structure	-	Mechanical cooling (split system air conditioning)	[47]
14.*	*Turin, Italy*	Library or learning centre	–	19th Century	*2006*	*4*	*2548*	Central core Load-bearing brick masonry Wooden roof with tile coverage	Assumed double glazing Venetian and roll blinds with schedule	Mechanical ventilation Air-cooled chillers	[22]

climate change and should receive adaptation priority [26], or to estimate changes in whole-campus energy demand [27,28], whilst other studies intend to provide more accurate depictions of individual building future performance [29,30]. Typically, the former research intentions align with the use of archetypal representatives, whilst the latter uses more detailed disaggregated modelling techniques.

On the use of archetypal representatives, Zhai and Helman [26] use primary building function to reduce a campus to a small set of representative buildings for predictions of future performance, under the assumption that energy use intensity (EUI) differs greatly by use type. Findings indicate halls of residences to experience the greatest increase in electricity peak demand (4–27 %) for the period 2070–2099 and laboratory buildings to experience the lowest increase (0–5%). However, specific factors driving this differentiation are not relayed through the analysis [26]. It could be anticipated that laboratories and ICT facilities, with typically high internal heat gains and resulting EUIs [31], would be particularly susceptible to the impacts of global warming. Unregulated energy consumption and inconsistent peak load requirements pertaining to laboratory equipment use can make these buildings difficult subjects of study, particularly those built prior to the integration of smart energy management systems for sub-metered energy consumption. As of yet these building typologies are underrepresented, with several authors selecting office spaces for more straightforward detailed analyses [9,24,32].

The use of such simplified archetypal representatives can be a key limitation of climate change impact studies, particularly for modern HE buildings, as they can differ greatly in terms of geometric shape, materials, systems configuration, even when classified as the same use type. Shen et al. [33] provide the example of laboratory buildings at the University of Pennsylvania, with such diversified window-wall ratios (WWRs), use schedules, equipment types and thermal capacities, that the resulting variance in EUI is large. In addition, HE buildings often have multiple primary functions [9,32,34], thus findings from climate change impact assessments can be misleading if not reported at the disaggregated zone-level [26,30]. Several studies utilise space-functionality percentage to account for this, formulated from zone area and use classification [35,36]. Whilst utilising these factors as predictors of annual energy consumption will not capture all variations in HE building design, it can be argued that space-functionality percentage does accommodate several important predictors such as occupancy patterns, building equipment and building size [35]. Nonetheless, climate change impact studies could benefit from more extensive building monitoring and disaggregated calibration techniques to capture typical occupancy profiles over a longer timeframe [37]. A greater focus on detailed, real-world case study scenarios could provide more robust evidence on the performance of HE buildings under future climates [38].

3.1.2. *Construction age and styles*

Existing studies capture a diverse range of building characteristics and thermo-physical properties, ranging from English Classism to post-modernism architectures [33,48]. They also vary significantly in construction age, reflecting the evolving contemporary building standards for energy efficient design [24,41,48]. Case studies (CS)1–3 feature traditional, British-influenced architectural elements; high thermal inertia, brickwork and stone masonry and relatively low glazing ratios [33,40,41]. The concept of thermal massing appears during the 1960s and 1970s through brutalist-inspired university architectures around the world [49], substituting brickwork masonry with heavyweight concrete structures. The concrete architecture that dominated Britain's post-war landscape initiated a wide-spread reliance still notable in modern construction techniques [50,51]. Increased recognition of the high grey energy content of extensive concrete use prompted the notion of leveraging thermal mass of existing buildings' designs, whilst adopting lower-embodied carbon alternative materials where possible [52]. This concept was demonstrated during the renovation of the Solar Energy and Building Physics Laboratory (LESO-PB) building in 1999; the refurbished timber façade sequesters carbon through its life-cycle [53], with reference to the vernacular architecture of the Schwyz canton [54].

HE buildings constructed between 1940 and 1980 account for approximately 40 % of the UK stock [16], and represent a major energy challenge due to typically high U-values and infiltration rates [22,55,56]. Retrofitting leaky, international style buildings can achieve high thermal performance during the heating season, but often intensifies overheating during summer months [57]. University buildings constructed in developed nations post-1970s energy crises were held scrutiny to newly-implemented building energy performance codes [58], instigating a wide-spread uptake of double glazing amongst other energy conservation measures [59]. As in 1950–1970, the innovation of extensive glazing through curtain wall systems remained popular [59]. However, developments in glazing efficiency resulted in systems with improved thermal insulation and light transmittance to provide high levels of natural light [59]. Overall, the period represented progress towards a more energy-conscious era, achieved mainly through thermal insulation and airtightness.

The highly glazed south façades of CS7-8 reflect the evolving priorities since the early 2000s [30]. 'Active' south façades had previously been used to encourage solar heat gains, with the aim of reducing heating load requirements [41]. However, increasing concern over summertime overheating led to the implementation of deep reveals and localised external shading, as in CS9-10 [28,48], often forming defining architectural features of more recent university building designs. Advanced shading and glazing geometries can be designed to encourage gains from the low winter sun whilst moderating peak summertime solar gains. Unlike the extensive curtain walling systems previously adopted [24,60], recent HE architectural developments often aim to limit glazed areas and avoid full height glazing, particularly on south-oriented façades, to restrict solar gains. In accordance with new building code developments for overheating, this reflects increased awareness of the importance of less glazing, more shading in order to handle extreme heat events [10].

3.1.3. Construction age and deterioration

Since many building components deteriorate over the building lifecycle, age can act as an important determinant of building performance under future climates [22,35]. Building ageing can negatively affect future energy performance by amplifying the increase in cooling loads under a warming climate, whilst also countering the reduction in heating loads [22]. Studies have indicated a high sensitivity of future energy use to a range of building ageing parameters, particularly HVAC equipment efficiency degradation [22]. Shrinkage, deterioration and thermal bypass of insulation can also result in higher U-values over a building's design conditions [22,61]. The impact of energy loses through the building envelope due to higher window and roof U-values is still expected to be a predominant driver of future campus energy demand for heating-dominant regions, despite a warming climate [35].

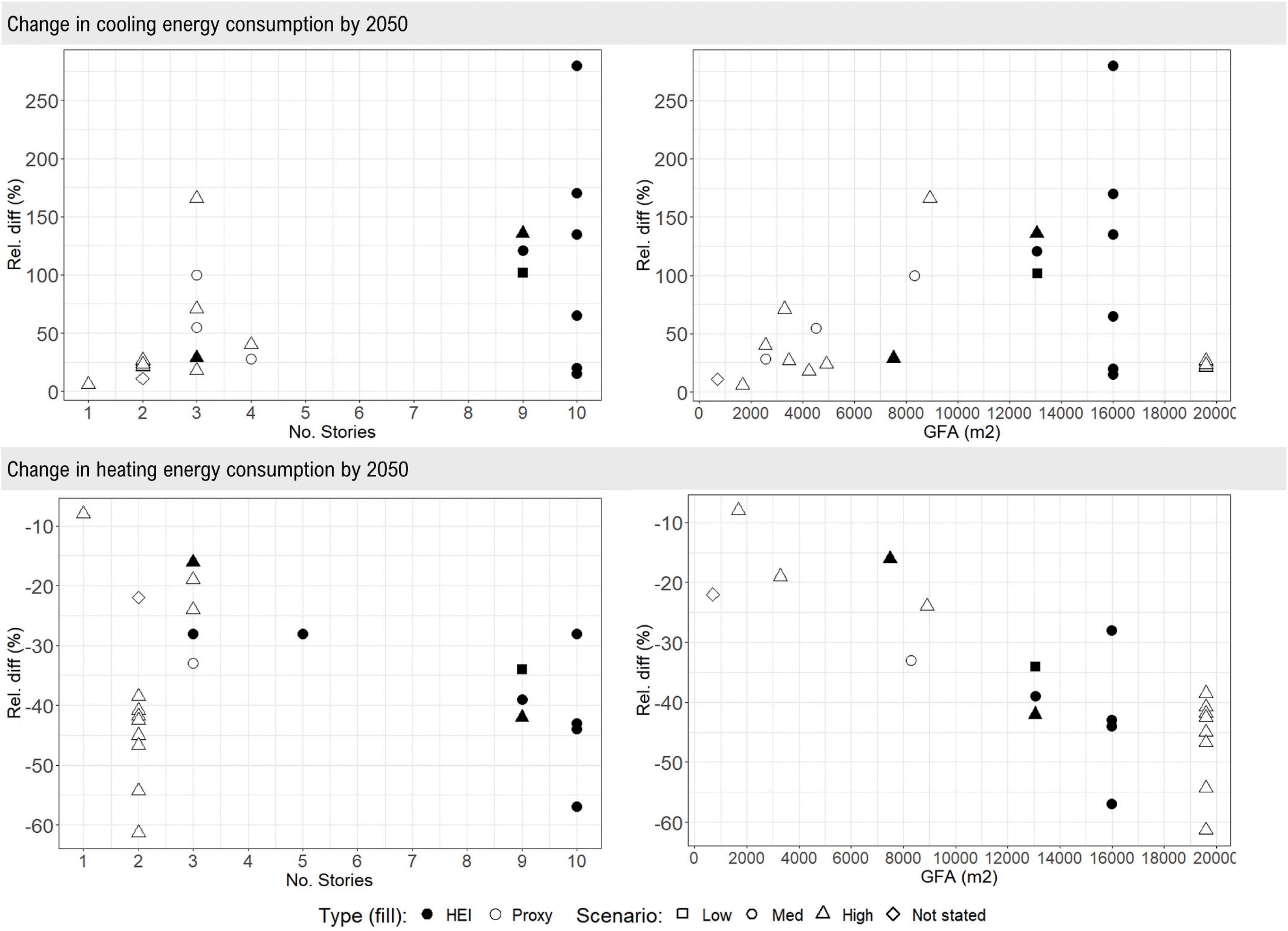

Fig. 4. Changes in predicted energy consumption, from the baseline year to 2050, by number of building stories and GFA (m2). Baseline years range from 1961 to 2020. Secondary schools, libraries and laboratories included for proxy building analysis [67–75]. Abbreviations: Gross floor area (GFA); relative difference (Rel. diff).

3.1.4. Building geometry

The post-war period also instigated a movement towards building vertically for urban redevelopment. Previous research indicates that high-rise structures, associated with urban UK HE buildings built during the mid-late 1900s (e.g., CS4-5) [62], are likely to be more susceptible to the effects of climate change [63]. Fig. 4 represents predicted changes in energy use by 2050 (baselines 1961–2020) for HE institutions included in this study alongside proxy schools, libraries and laboratories. Relative changes in cooling energy consumption range from +6 % (1-storey; high emission scenario) to +280 % (10-storey; medium emission scenario), both UK studies. Taller buildings may be more vulnerable due to exposure to the elements [24], with top floors of high-rise structures offering less protection to heat during hot periods [63]. In addition, many high-rise HE buildings from this period have matching façades on all elevations (e.g., CS4-5), not accounting for solar geometry. Whilst tall buildings can have better scope for daylight penetration and natural ventilation, fabric and infiltration heat losses are typically higher [64, 65]. Resultingly, current building standards encourage a low surface area to volume ratio (A/V ratio ≤ 0.7 m^2/m^3; form factor ≤ 3) [66], but compactness often aligns with deep-set floor plates. Shallow plan structural layouts, e.g. CS2, can benefit more significantly from the use of passive cooling strategies (CIBSE, 2005a), such as cross-flow and single-sided ventilation, to mitigate overheating under future climates. The trade-off between a low form factor and passive ventilation-enabling structural layouts should be investigated when designing for future climates.

3.1.5. Retrofitting

Retrofitting offers the potential to mitigate increasing energy loads due to climate change; this has been acknowledged in several HE case studies [22,35,76]. Waddicor et al. [22] model the implementation of a number of retrofit strategies during the year 2040 for a heating-dominant Italian region, with chiller replacement having the greatest impact (25 % decrease) in final energy consumption from the year 2030. A combination of retrofit measures, including changes to the chiller coefficient of performance, lighting, and glazing type, showed a potential decrease of 87 % in final cooling energy use in 2040 compared to the base case value for the same year [22]. Increasing expanded polystyrene wall insulation thickness from 100 mm to 150 mm had no significant improvement in the building's overall energy performance. The authors instead suggest a focus on improving the glazing transmittance g-value in higher latitudes of Europe, where heating degree days are generally still more numerous than cooling load days [22]. Yau et al. demonstrate the power of retrofit in increasing the resiliency of HE buildings to climate change, with results indicating a 38 % lower peak cooling load in 2050 for the new wing of a library in Malaysia versus the old wing, when normalised by respective floor areas [40]. This reiterates that future HE building performance cannot be classified by function alone, although it is difficult to disaggregate the relative performance of each retrofit measure when observing post-retrofit performance. Bahaj and James [57] model the addition of solar control and night purging strategies to a poorly performing UK HE building, suggesting that high internal loads due to occupancy, computing and artificial lighting will make it difficult to achieve adequate thermal performance in free running HE buildings under future climates. 'Soft' adaptations, such as changes in working hours and management of user behaviours and expectations, may become increasingly necessary to complement physical retrofit of existing buildings.

3.1.6. Passive design strategies

The majority of passively cooled urban HE case studies appear to experience significant overheating under future climate scenarios, even in cooler UK climates [24,28,41]. Jentsch et al. and Abu Aisheh et al. observe the future performance of naturally ventilated tower block buildings in two UK cities, displaying architectural properties typical of many HE buildings built in the 1960s and 1970s [24,32]. Results suggest levels of overheating are excessive even under current climate conditions and this will be significantly impacted by projected changes in the UK climate. The social sciences building in Sheffield, UK also experiences considerable overheating under present day climates, despite the implementation of advanced natural ventilation strategies, such as passive stack flow ventilation and night-time cooling [60]. This may be due to the highly glazed South façade and South-facing atrium applied to provide passive solar heat gains to the system. For climates such as the UK, a trade-off often exists between wintertime and summertime energy conservation measures, and whilst passive strategies can significantly reduce energy loads, mechanical solutions will often be required to meet the threshold comfort levels throughout the entire year [77].

With appropriate control, thermal mass can reduce internal temperature fluctuations both in summer and winter, reducing peak energy demand and facilitating load shifting [78,79]. However, when reliant on nightime purging to release heat stored throughout the day, the success of this technique correlates with the strength of diurnal swing. Research indicates that rising average temperatures due to climate change will limit the free cooling potential of thermal mass, necessitating the use of mechanical cooling mechanisms to achieve the desired effect [77]. Current industry guidance recommends accounting for future daytime and nighttime temperatures when pursuing a thermal mass strategy [52]. This highlights the importance of evaluating building performance against future climates, with many strategies designed to prevent overheating under present-day conditions potentially being insufficient to oppose future increases in summertime temperatures. An additional consideration for implementing high thermal mass within a HE building context is the extensive warmup period, possibly resulting in temporary thermal discomfort and high energy loads [80]. Since university buildings tend to experience low occupancy over extended holiday periods, the warmup process may be more frequent and energy-intensive than with other building typologies.

Advanced concepts behind low and nearly zero-energy buildings (nZEBs) provide opportunities to understand the performance of modern construction techniques under future climates. Rey-Hernandez et al. [29] evaluate the performance of the highly-accredited zero-carbon and nZEB laboratory building, supporting a range of energy conservation measures and renewable energy strategies for on-site generation, including a photovoltaic (PV) curtain and biomass-fuelled combined heat and power systems. Climate adaptive measures are also incorporated into the southern bioclimatic façade, such as auto-shading windows, green roofs, and natural ventilation with geothermal recovery. Despite existing climate adaptive strategies, results indicate a 30 % and 80 % increase in cooling loads for 2050 and 2080 respectively [29], reiterating the need for low-carbon energy sources as well as energy efficient designs. Nonetheless, a lower starting point for energy consumption means that this percentage increase is still relatively small compared to buildings with less advanced adaptive features.

3.1.6.1. Systems configuration. Climate change impact studies on actively cooled HE buidlings can help to explore contextual issues surrounding increased cooling demand, such as the suitability of system sizing and security of energy supply [34]. Several studies align their findings on future energy use with observations of a real HE facility [26, 29,40]. Generally, existing safety margins for system sizing are expected to be sufficient to handle increased cooling loads due to global warming, owing to a tendency for considerable oversizing factors in non-domestic buildings [34,40]. Part-load operation and run-time fractions could be more prominent issues regarding systems design, although the renewal of building services at the end of their 15–20 year lifetime provides facility management with the opportunity to deal with any changes in climate conditions and to introduce more efficient technologies [34].

As campuses transition towards increased on-site intermittent renewable energy generation, security of supply may become a greater concern, particularly due to the increasing frequency of extreme weather events [81]. This is reflected in a study of the EPFL campus in Switzerland [27], with fossil-fuel powered co-generation gas turbines required as a backup plant to renewable supply. Similarly, Zhai and Helman indicate that additional energy generation plant could be required when considering the campus-scale increase in cooling demand under a high-emission scenario [26]. Rey-Hernandez et al. describe how the increase in cooling loads due to climate change could be managed for a zero-carbon building by increasing the burning of biomass as a back-up supply to an adsorption cooler [29]. The potentially greater reliance on carbon emitting back-up supplies warrants quantification of the requirements for alternative renewable and sustainable solutions, such as energy storage, to replace the contribution of gas turbines.

For university campuses located in densely populated urban locations, on-site energy generation may be limited to relatively small amounts of roof mounted PVs, wind turbines and emergency systems [82,83]. Thus, the reliance on distributed power networks will be intensified over the next century to meet increased cooling loads due to global warming. In addition, predicted shifts due to electrification of heat and transport will also significantly impact overall and peak demand, placing strain on local grid networks [84]. A campus that is heavily reliant on distributed electricity supply may require additional substations to meet increased demand, particularly under extreme hot weather events. The wider issue remains around energy security, with limited grid capacity for full conversion to entirely electrically-powered buildings [84,85]. Therefore, a campus' role in improving energy security should also be in enhancing capacity for demand response.

Table 4
Overview of research themes and methods for studies addressing campus urban geometry and scale.

Method	Location	Research Theme	Ref
Coupled indoor-outdoor simulation tool	Sheffield, UK	Evaluating the combined impact of climate change and urban microclimate on overheating and peak chiller load consumption.	[30]
	New Cairo, Egypt	Evaluating the combined impact of climate change and urban microclimate on average indoor air temperatures.	[41]
	Lausanne, Switzerland	Modelling reductions in campus energy demand through stock-level renovation scenarios.	[27,28]
		Understanding the implications of various future weather data sets on campus outdoor temperature and energy demand	[89]
Regression-based forecasting model	Philadelphia, US	Modelling the relative performance of spatial and environmental variables in predicting future campus electricity and chilled water consumption	[35,90]
	Beijing, China	Modelling the relationship between temperature and electricity consumption in student residences to predict future energy consumption under a range of climate scenarios	[91]
AI-based forecasting model	Florida, US	Predicting hourly campus energy use based on buildings' space functionality percentages and thermophysical properties.	[36,92]
Coupled urban heat island -climate change workflow	Massachusetts, US	Integrating urban heat island effect and climate change within urban design workflow to predict campus thermal comfort and energy use	[93]
Coupled stochastic-deterministic approach	Michigan, US	Evaluating the impact of 4 reference climate models on cooling energy consumption and peak cooling demand for 5 representative campus buildings with varying use functions.	[26]

3.1.6.2. Urban geometry and scale. De Wilde and Tian highlight the research potential for a larger scale approach to conduct climate change impact studies on an urban, regional or even national level [34]. Universities are a collection of buildings that can operate as an energy community [86], highlighting the importance of an urban neighbourhood approach. This is important for planning climate change adaptation and energy networks at scale, but also because the performance of individual buildings under a changing climate will be affected by the local microclimate and urban geometry [87]. Several studies presented in Table 4 have developed the concept of campus-level coupled outdoor-indoor environmental simulation frameworks, that aim to account for the changing urban microclimate [30,44]. The coupling methodology tests the hypothesis that the energy demand of a building is tightly connected to the local microclimate through an urban simulation workflow [88]. For the EPFL campus in Switzerland, results suggest total heating demand would decrease less under future climate scenarios due to the cool air pool effects at the site and reduced solar gains related to the urban density [27,88]. The study also indicates an increase in cooling demand, with microclimatic effects exasperating the rise in temperatures due to climate change [27]. The resulting 42 % predicted increase in peak demand was considered to have significant implications on energy system sizing [27]. Incorporating topographic features of the local environment can provide a more accurate assessment of climate change impacts, however, also introduces additional uncertainty by assuming detailed prior knowledge of campus building plans over several decades.

Several methodologies have been adopted to achieve the campus-level scale for climate change impact studies. Nik et al. utilise typical properties of buildings built during the four main construction phases of the EPFL campus to estimate the characteristics of all campus buildings [89]. Fathi et al. extrapolate the forecasted consumption for a set of 8 'representative' buildings to the entire University of Florida campus (>900 buildings), based on space functionality percentages [36,92]. Similarly, Zhai and Helman classify an entire HE estate into 5 representative buildings, based on function and EUI [26]. Extrapolating based on small sample sets is likely to result in large error margins due to variations in thermophysical properties for buildings of the same space use function [33]. Im et al. reduce the case-study area to a proportion of the campus (48 buildings) for which sufficient data was available [35]. Despite the larger sample number, there is little discussion on the influence of typology on future building performance, with analyses presented in terms of average consumption across all 48 buildings [35]. Detailed characterisations of individual buildings could help to improve the accuracy of campus-level analysis.

3.1.7. Location

Mid-latitude and semi-arid regions are projected to see the greatest hot day temperature increases, whilst many northern-most regions are likely to experience the highest temperature increase of the coldest days [2]. Ignoring the influence of locational building and systems design variations, this could be interpreted as an expected trend of higher increases in cooling loads and lower heating load increases for buildings closer to the equator. Yet this is not evident from the results of the HE and proxy studies, with no clear relationship observed in Fig. 5 between absolute distance from the equator and changes in cooling or heating energy. This may be indicative of other attributable factors that override the warming effect; buildings under investigation have been designed specifically for the climates under which they were built and climate

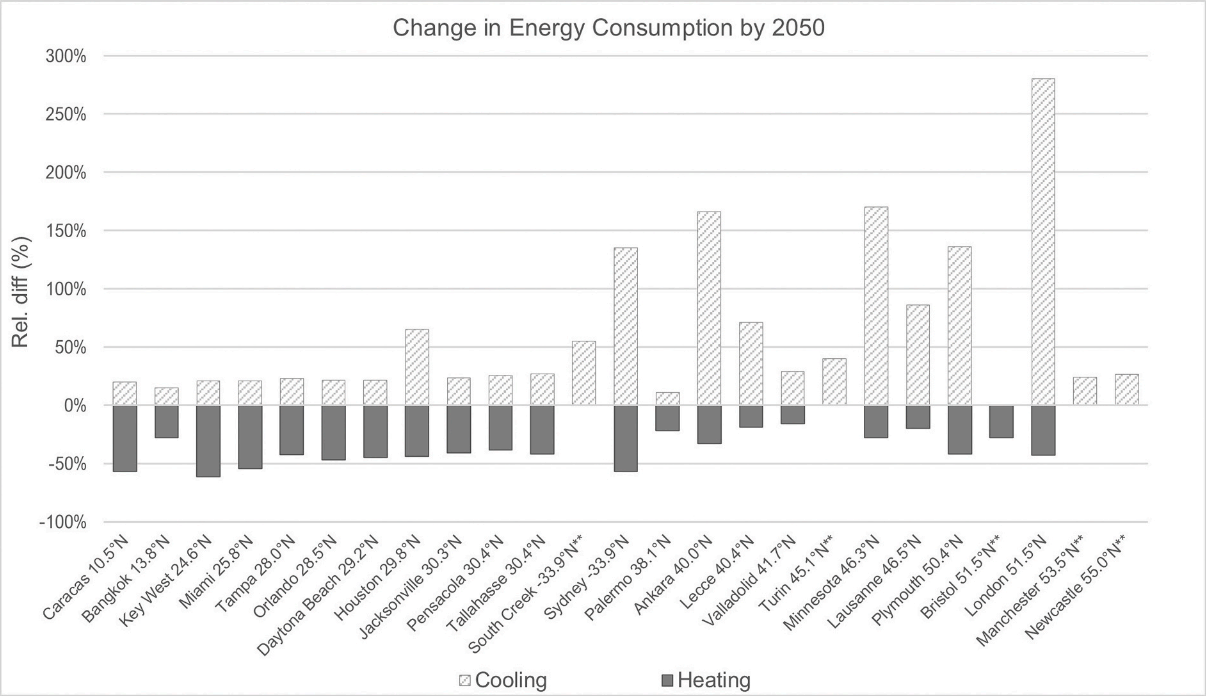

Fig. 5. Change in energy consumption from baseline to 2050 for various locations, sorted by absolute distance from equator (lowest to highest). Baseline years range from 1961 to 2020. **No heating/cooling energy consumption data available.

adaptive strategies leverage properties of the local microclimate. For example, geographical disparities in wind speed and air temperatures will define the potential for stack flow ventilation [94]. Furthermore, the adaptive comfort standard acknowledges occupants as integral components of a self-regulating system, using adaptive measures to modify their person and environment in order to achieve a state of comfort [95]. Thus expectations for set-point temperatures in the modelled buildings may vary by location. Evidence from case studies conducted in cooler mid-latitude climates of the northern hemisphere, such as the UK, suggests that HE buildings are ill-equipped to handle this temperature rise [24,28,41]. This may reflect the past prioritisation of energy conservation measures to reduce heating loads, with less consideration given to potential future overheating trade-offs in the design process.

Evidence on the resilience of HE buildings under current climates in hotter equatorial regions can aid understanding of the performance of certain techniques in withstanding extreme heat. For Middle-Eastern, sub-Mediterranean and South Asian climates, research primarily focuses on the prevention of heat entering system external boundaries. The design conflict between direct heat gain, glare and lighting quality demonstrates one of many increasing design challenges under extreme heat. Given the importance of sufficient natural lighting in educational environments, and the abundance of daylight in many equatorial regions, the need to optimise visible transmittance (VT) whilst minimising solar heat gain coefficient (SHGC) has been noted by several authors [96–99]. Suggested measures include: window films with VT values adjusted according to the degree of shading (0.45–0.55 for moderately well-shaded surroundings) [96]; the installation of replacement insert low-e glazing [96,99]; soft or sputtered low e-coatings [96]; ‘selective glazing’ [98]; and algae windows [97]. The addition of window films (VT 15 %; SHGC 0.38) to HE office spaces in Kuwait was estimated to save 416 kWh of cooling electricity consumption between June–August relative to regular double glazing, approximately only 1 % kWh and CO_2 savings [99]. Etzion et al. observe the efficacy of a double-skinned polycarbonate sheet that selectively transmits solar radiation; with prisms allowing for internal reflection, transmissivity varies as a function of the angle of incidence solar radiation [98]. The mechanism appeared less effective than manufacturers specifications for a multi-functional HE building in a hot, desert climate. Negev et al. simulate the impact of incorporating living microalgae windows into the building facade of a HE office space in Israel; using empirically derived values for thermo-physical and visual properties, the authors estimate energy savings of up to 8–20 kWh/m^2/year for East, West and South-orientated zones, respectively. Further research and innovation is required for these novel technologies to become cost-effective, particularly for use in less economically developed, hot-climate regions.

Several simulation studies reaffirm evidence on the positive role of urban greening on campuses, even under extreme heat [100–103]. Al-Omary and Alsukkar simulate the heat absorbance potential of a green wall in a university campus in Jordan, suggesting energy savings may be possible through urban heat island mitigation in dense urban environments [101]. For climates with hot summers and cold winters, the integration of a green wall system with a double-skin façade has been proposed with inter-seasonal benefits [102]. Simulated on a library building in South Korea, the mechanism demonstrated the combined potential of promoting airflow whilst reducing thermal bridging (up to 3.97 % and 12.62 % reduction in heating and cooling loads respectively) [102]. However, the potential for greening in dry and arid regions is increasingly limited; alternative energy conservation measures investigated for these HE institutes include earth berming, down-draft cooling, hybrid mechanisms for hot-air supply and smart materials (e.g. bi-metals or memory alloys) for shading [98,104]. Solar heated air systems and evaporative cooling can provide successful and cost-effective means for the provision of thermal comfort [98]; optimisation of the air-flow rate through the tower is critical in ensuring a higher cooling output. Several design conflicts were noted resulting from improper use of cooling mechanisms by occupants in hotter climate regions [96,105,106], with suggestions for achieving further energy reductions through automation e.g. building automation and control systems and HVAC algorithms based on occupancy and adaptive comfort temperature [107,108].

3.1.8. *Case study comparability*

From this classification process, it is evident that HE climate change impact case studies are limited and there are some clear research gaps relating to parts of the building stock that have not received sufficient study focus. This includes a fuller breadth of HE typologies, with greater research required to understand the archetypal performance of non-office spaces, as well as a wider range of form factors, under various emission scenarios. The complexity and variability of HE building design means that any single driver of climate change resilience will be influenced by a number of other confounding and uncontrolled factors, such as internal gains, use patterns and external climates. The combination of a low study number and difficulty disaggregating these key determinants results in a limited evidence-basis for observing relationships between HE building design characteristics and future performance.

3.2. Modelling assumptions and performance indicators

Despite a limited evidence basis for the performance of HE buildings under future climates, modelling assumptions and performance metrics have been reviewed in this section, with the aim of identifying common procedures and discrepancies in defining climate change resilience. A widely accepted approach to climate change impact studies is to identify three key aspects: the case study, climate data, and performance criteria [4,13].

3.3. Climate models

The choice of climate model, scenarios and probabilistic projections incorporated into the modelling process can have a considerable impact on model outputs [26,109]. Across HE case studies, climate models and observed scenarios vary considerably, based on geographical differences and recentness. Climate models are frequently updated based on advances in climate change science and policy interventions that modify expectations of future warming [110]. As a result, study outcomes can be limited by outdated models and idealistic assumptions. For example, the global climate model adopted by Degelman [9] suggests larger increases in daily minimum temperature than daily maximum temperature as well as increases in cloud cover, both of which have been directly contradicted by climate models used in other studies [24,46]. This is likely due to the time difference between studies and developing picture of the planets changing climate systems.

Several authors also highlight the large variances in campus-level energy consumption when considering multiple future climate scenarios (e.g. low, medium, high emission scenarios) [26,45,109]. Zhai and Helman demonstrate how this uncertainty can lead to an increase in predicted campus cooling energy ranging between 5 % and 90 % for the period 2070–2099 [26]. Tian et al. state that the uncertainty in cooling energy consumption owing to climate predictions is significantly higher than that of heating energy [45]. In any case, the varying temperature profiles act as the greatest cause of uncertainty in building thermal and energy performance under future climates [35], and since no single emission scenario is more probable than another, it is recommended that the full set of scenarios is used to examine sensitivity to different levels of climate change [111].

An additional discrepancy arises from the timescale of projections. The majority of studies use a 2050 timeslice or similar as a critical reference point to demonstrate climate change impact, which has the advantage over late-century projections of greater certainty [14]. However, this timeframe does not usually capture performance over a typical studied building lifespan (60 years) [112], thus the longevity and resilience of refurbishment or retrofit scenarios is often not tested. The probabilistic climate profiles (ProCliPs) introduced in 2014 recommends the use of three time periods (2020, 2050, 2080), three emissions scenarios and five probability levels [14]. However, attempting to capture such a vast number of future weather years whilst still making comprehensive assessments can be a key challenge. For future climate analysis to be regulated through the use of probabilistic projections, the issues of liability and litigation for failing environmental performance criteria must be addressed by building regulations. Probabilistic projections offer significant advantages over deterministic in capturing climate change risk due to uncertainties [111], but can significantly increase the complexity of the problem. Further research is warranted on methods to reduce the modelling effort required to interpret uncertainty, rather than simply reducing the number of considered scenarios. For example, genetic algorithms can provide a useful tool to evaluate the performance of climate adaptive strategies more rapidly across a range of scenarios.

3.4. Thermal performance metrics

No established framework exists for performing climate change risk assessments for the environmental design of buildings [111], evidenced by the range of thermal performance metrics in Table 5. Many outcomes have been reported for specific simulation dates and times, considerably reducing the potential for cross-study comparisons [30,60,87]. In addition, overheating performance metrics primarily focus on fixed threshold values in accordance with the now withdrawn CIBSE TM36 guidance on climate change and the indoor environment [113]. In an accompanying appraisal of TM36, de Dear [13] describes occupants as fundamentally adaptive beings and suggests this to be a missing concept in climate change impact assessments. The ‘adaptive comfort model’ was introduced as a new standard for designing and operating naturally-ventilated buildings within a wider comfort range, based on the relational perception of thermal comfort relative to the external temperature [114,115]. Nearly all climate change impact studies conducted in UK-based HE institutions were published prior to the release of CIBSE TM52 in 2013, which introduced the adaptive comfort standard to the UK [116]. Consequently, there is need to improve understanding of future HE building thermal performance against modern overheating standards, including ASHRAE-55 and EN-16798 [114,117]. Recent implementations of CIBSE TM59 design methodology for overheating risk assessment in homes and Approved Document Part O demonstrate increased awareness of the importance of overheating analysis even in heating-dominant regions. These regulations apply to domestic buildings only and future climate analysis is not a requirement [10,118].

3.4.1. Energy performance metrics

Studies captured by this review primarily focus on energy

Table 5
Thermal performance metrics and results of HE climate change impact studies.

	Location	Performance metric	Unit	Scenario	Diff	Ref
1.	United Kingdom	DSY average daily indoor air temperature	°C	Med-high	+2.0	[24]
		DSY maximum daily indoor air temperature	°C	Med-high	+2.1	[24]
2.	United Kingdom	% exceedance above 28 °C	%	Low	+6	[32]
		% exceedance above 28 °C	%	High	+7	[32]
3.	United Kingdom	Indoor air temperature on 24 July	°C	Not stated	+0.27	[30]
		Average indoor air temperature on 6 July	°C	High	+1.7	[44]
4.	United Kingdom	Average indoor air temperature on 6 July	°C	High	+1.04	[44]
5.	United States	Predicted mean vote	PMV	Med-high	NA	[33]
6.	Switzerland	Predicted mean vote, July	PMV	B1	+0.85	[28]

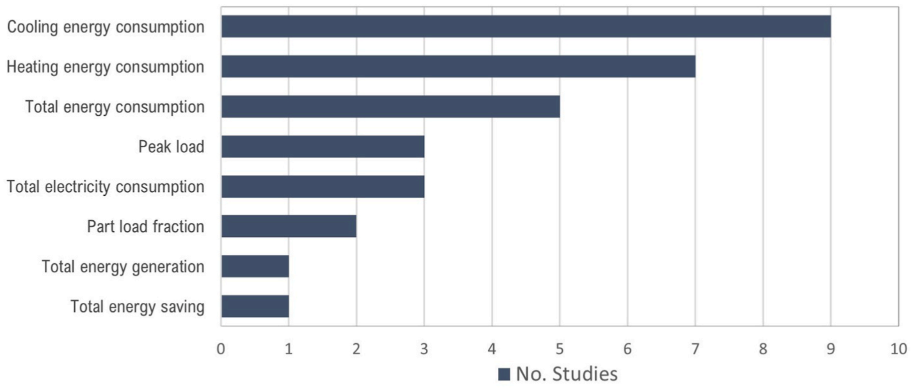

Fig. 6. The various energy performance metrics used as predictors of future HE building performance, and the number of studies using each metric.

performance metrics as detailed in Fig. 6, including total and disaggregated energy consumption, peak loads, part load fractions and energy generation. The CIBSE Energy Benchmarking Tool and TM46 provide standards for evaluating operational energy use in HE buildings, expressed in terms of cumulative EUI ($kWh/m^2/yr$) [21,25]. Despite this, only 24 % of studies normalise energy use towards gross square meter floor area, obscuring comparisons with other buildings and campuses. Previous research conducted in schools has demonstrated how the number of students can also be a key determinant of electricity consumption (i.e. kWh/student) [119], but can lead to significant discrepancies when compared to results as measured by EUI [120]. This raises the question of whether the existing EUI metric is the most suitable for the evaluation of energy performance. University buildings often have large intra-day and seasonal occupancy variability; normalising energy use per square meter may fail to capture the dynamic and transient nature of these spaces. More extensive research is required to understand the stronger predictor of energy use in HE buildings, helping to minimise non-climate related uncertainties in climate change impact assessments.

Another difficulty in comparing results arises from the inconsistent reporting of primary versus final energy. Primary energy factor, adopted by the government in Part L building regulations [121], is a dynamic property that evolves with the changing fuel supply mix in any given region or country over time [22]. Whilst reporting on final energy consumption makes it easier to run comparative analysis, the discussion of site-to-source conversion factors is an important one when considering the dynamic state of the fuel supply over the next century, with important implications on the suitability of climate change adaptation measures. One option is to estimate change in primary energy factor using dynamic empirical data. Waddicor et al. utilise primary energy factors derived from fixed, moderate, and high penetration of renewables by 2060 (2.36, 1.65, 1.16 respectively) [22]. However, the authors do not consider the causal relationship between the primary energy factors and the emission scenarios observed. Further consideration could be given to the fact that the emission scenarios are formed in part as a result of assumptions on the changing fraction of energy sources.

Whilst energy performance metrics tend to focus on changes in energy consumption within the HE sector, a less extensively researched area is climate change risk to exportation of generated supply. Rey-Hernandez et al. observe how, for a nZEB in Spain, surplus electricity generation by PVs that was previously fed back to the grid is entirely consumed within the building due to increased demand [29]. In this way, climate change could counteract the benefits of on-site renewable energy generation and storage, such as security of supply and feed-in-tariffs. Further consideration could be given to the fact that transitioning to renewable-based generation can make the supply system more vulnerable to climate variability and changes [122]. In Europe, energy generated from solar PV is estimated to change in the range of −14 % to +2 % by the end of the century, with the largest decrease in Northern countries [122]. Wind energy supply is projected to decrease in Mediterranean regions and increase in Northern-Central Europe but with greater inter-annual variability [123]. Whilst these studies do not indicate any overall major disruptions to supply, the various implications on energy generation underline the importance of a system dynamics approach to climate change adaptation frameworks.

3.4.2. GHG emissions performance metrics

Operational energy use figures can be converted into GHG emissions [46], to measure and mitigate a building's carbon impact. GHG emissions are typically reported as equivalent mass of carbon emissions per kWh energy used ($kgCO_2e/kWh$) [124]. This metric has the advantage of offering a universal method for comparing the efficiency of different systems [34]. However, it is often difficult to apply to climate change impact assessments due to the changing carbon intensity factors of the supply mix; a fixed carbon emission factor over a timespan of several decades, as adopted by Tian and de Wilde [46], is no longer a reasonable assumption. In 2016, 52.5 % of the UK HE sector energy mix was supplied by natural gas [125], for which the decarbonisation rate is difficult to predict due to uncertainties in hydrogen and biomethane penetration of the gas network. The decline in electricity GHG emissions is also highly uncertain as it is strongly dependent on the changing fuel mix and rate of renewable uptake [126]. All scenarios developed by the UK National Grid predict a rapid decline of electricity carbon emissions in the early 2020s. However, the period for which net-zero emissions are eventually reached varies, depending on decarbonisation strategies and the successful implementation of bioenergy with carbon, capture and storage [126]. Moreover, the HE sector's energy supply mix and overall consumption is rapidly changing in response to decarbonisation initiatives, such as policy proposals for electrification of heat [125,127]. These factors complicate the predictions of operational carbon emissions under future climates and highlight the need for a flexible framework that can be adapted according to changing policies.

The operational energy decarbonisation rate will also impact the contribution of embodied versus operational GHG emissions [52,128], influencing the life-cycle carbon-intensity of climate change adaptation measures. Hawkins and Mumovic apply the emerging field of research on life-cycle carbon to the HE sector, finding embodied carbon currently contributes 6–23 % of total life-cycle carbon for new-build HE buildings [129]. In the UK, electricity sector carbon emissions reduced from 457gCO2e/kWh in 2010 to 138 gCO2e/kWh in 2021 [130]. If future operational energy is net-zero, the embodied carbon associated with refurbishment projects to provide low-energy means of cooling may offset the reduction in operational energy emissions [128]. With exception to Luo and Oyedele [39], studies that adopt GHG emissions as a metric for climate change impact have focused on operational carbon only [46]. The embodied carbon share of total life-cycle carbon is likely to increase as building operational carbon performance improves, highlighting that embodied carbon should also be considered as a key performance metric [129,131].

3.4.3. Cost metrics

Only three studies consider cost metrics as an indicator of building performance under future climates [26,33,39], despite the critical role that financial indicators play in the decision making process for any HE refurbishment. Zhai and Helman estimate that the growth in Michigan University campus cooling energy demand could range between $1-$8 million USD annually for the period 2070–2099 depending on the scenario observed [26]. The upper value is projected under a high emission scenario and represents an 85 % increase on current costs, suggesting that improvements to the campus cooling systems may need to be considered. Rey-hernandez et al. also assume a growth in maintenance and replacement costs owing to increased systems' operating hours, the extent to which warrants further research into life-cycle costs [29]. This is touched upon in research by Shen et al., where both retrofit costs and energy savings ($) are considered as optimisation parameters for the selection of climate change adaptation mechanisms [33]. Several dynamic variables should be considered to capture the uncertainty and risk related to future costs, such as increasing fossil-fuel price projections [132], and changes to the levelized cost of electricity due to an increasing penetration of variable renewable energy [133]. However, the volatility of the European energy market in 2022 highlights substantial uncertainties in anticipating future price projections [134]; the development of combined environmental indices that consider monetary value alongside additional metrics, such as carbon cost and social wellbeing, may provide greater stability in valuing long-term retrofit and refurbishment success.

4. Conclusions

This review has drawn on evidence of the resilience of individual HE case studies to future climates, whilst acknowledging several limitations, such as a low sample size and varied locations, building parameters and reported outcomes that prevent cross-study comparisons. Whilst most available studies came from North America and Europe, the trends observed may be noticed in other similar climate regions, and deepen understanding for policy and designers around the world dealing in HE design and management. The process has revealed several important insights about the state of the field, with potential implications for future research and practice.

1) Expand the research basis using standardised frameworks

The systematic review process revealed considerable variability in modelling input assumptions and performance metrics, significantly limiting the comparability of results. This is likely due to the lack of established guidance on conducting climate change impact studies resulting in little process standardisation. Where comparisons would be feasible between studies, the low study number means there is insufficient evidence to identify the key determinants of future building performance within the HE sector. Therefore, there is a need to expand the research basis for climate change impact by generating a standardised framework that can evaluate resilience on a per building basis, whilst being applicable to the wide-range of building typologies that reflect the diversity of the HE building stock. Climate change impact assessment frameworks should align with industry guidance where possible, for greater consistency across metrics, modelling approaches, and energy and overheating assessment methodologies [21,116]. In addition, adopting standardised baseline timescales in accordance with large modelled datasets, such as 1961–1990 (TMY2) or 1991–2005 (TMY3), would allow for improved cross-study comparisons. From an industry perspective, a key challenge for the standardisation of climate change impact frameworks will be contractual liability for failing environmental performance, due to the uncertainties of future climate projections. This is particularly pertinent considering the large number of stakeholders involved through all RIBA stages, from building design through to operation.

2) Incorporate uncertainty

There is great use in climate change impact studies for the built environment but uncertainty must be incorporated. Considering multiple climate scenarios can result in large error margins for predictions of cooling energy consumption, and even under a single emission scenario, total energy consumption change can vary widely between HE buildings and campuses. This review also revealed the many dynamic variables that are expected to change over time and should be considered for a more robust study of resilience e.g. climate models, climate scenarios, fuel mixes, site-to-source conversion factors, carbon emission factors and fuel prices. Studies that adopt fixed inputs from a single snapshot in time are no longer reasonable, as the assumptions behind climate change impact studies can quickly become obsolete due to changing policies, technological innovations and knowledge advancements. The development of a framework for climate change impact assessments should therefore operate as a scenario analysis tool, with a baseline that allows for layers of assumptions to be applied and updated in line with the fast-paced developments in climate change understanding and policy. To minimise risk associated with these uncertainties, design solutions should be optimised across a range of climate models, scenarios and timescales, and towards overall energy change, with predictions of heating load reductions accompanying increasing cooling loads.

3) Consider the buildings estimated life-cycle

The utilisation of several time periods, including longer term projections, can be useful in considering the impact of HE building ageing, retrofits and renovations over the buildings lifetime. A longer timeframe also allows for the rate of decarbonisation to be incorporated over the next century, with potential implications on the suitability of renovation measures. Sustainable methods for adapting buildings to future climates should consider the embodied carbon of implementing the renovation strategies themselves, since this comprises an increasing share of total life-cycle carbon emissions. Further research is warranted to understand the trade-offs between active and passive HE design strategies for climate change adaptation, in light of this evolving relationship between embodied and operational energy and carbon.

This work provides direction for the development of a more extensive evidence basis on the resilience of the HE building stock to climate change. The relevance of this may be of interest to design practices and governmental organisations, such as departments for education, with potential implications on future policy and HE design.

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CRediT authorship contribution statement

Eleni Davidson: Conceptualization, Methodology, Data curation, Writing – original draft, Visualization. **Yair Schwartz:** Validation, Supervision, Writing – review & editing. **Joe Williams:** Validation, Supervision, Writing – review & editing. **Dejan Mumovic:** Conceptualization, Supervision, 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

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

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