Climate Adaptation Strategies for Non-Domestic Buildings: Evaluating Retrofit and Adaptation Measure Performance Under Future Weather Scenarios Using Building Energy Simulation

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ABSTRACT

Climate change poses unprecedented challenges for buildings through rising temperatures and increased thermal discomfort. This particularly affects the UK, where most buildings predate adaptation standards, creating knowledge gaps about long-term performance for structures expected to operate 50-100 years. Simultaneously, while urgent net-zero targets are driving rapid implementation of energy-saving retrofits, their effectiveness under future climate conditions remain unclear. This study has two objectives: investigating how future climate affects building energy performance and thermal comfort while evaluating traditional retrofit effectiveness for climate adaptation, and identifying when these strategies become insufficient, requiring additional measures for adequate thermal comfort. The methodology uses building energy simulation on three Oxford case study buildings representing diverse typologies and construction periods. Energy performance and thermal comfort are analysed under historical (2022-2024) and projected future climate data (2025-2080) across multiple scenarios: no retrofits, net-zero carbon measures, and climate-specific adaptation strategies. Results reveal that building type, age, and design decisions significantly influence climate resilience, with newer buildings not necessarily providing better future thermal comfort than older ones. Traditional energy-saving retrofits reduce consumption but can worsen summer comfort in certain configurations, highlighting gaps between current practices and future climate demands. This work provides a replicable framework for quantifying long-term effectiveness of design decisions and determining optimal timing for secondary interventions, informing investment strategies for building stock resilience.

INTRODUCTION

The built environment faces two interconnected challenges: achieving net-zero carbon targets while ensuring buildings can withstand future climate conditions (Baniya and Giurco 2025). In the UK, under a high emission scenario, hot summer day temperatures are expected to increase between 4°C (39°F) and 7°C (45°F) by the 2070s (Met Office 2022), creating a mismatch between building lifespans (~50-100 years) and the timescale of global warming (de Wilde and Coley 2012). Buildings being retrofitted today must therefore perform effectively under significantly different climate conditions than those for which they were originally designed (Robert and Kummert 2012). For example, rising temperatures will drive significant increases in air conditioning (AC) use, potentially counteracting energy reductions achieved through net-zero carbon (NZC)

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retrofits. Without proactive adaptation planning, NZC retrofit investments may prove inadequate or counterproductive under future conditions.

Building energy simulation (BES) is a valuable tool for testing net-zero and adaptation strategies (Crawley 2008). However, current BES practices fall short in several ways. While widely used with current weather data, BES application with future weather remains limited (de Wilde and Coley 2012). Additionally, most BES research relies on single-year rather than multi-year calibration, essential for projecting performance outputs over extended periods of time (Royal et al. 2025). Existing studies also focus mainly on basic indicators (e.g. heating/cooling energy use, overheating compliance) rather than adaptative thermal comfort metrics like Predicted Mean Vote (PMV), needed for developing nuanced strategies (de Wilde and Coley 2012). Finally, while many studies have focused on deriving BES-specific UK future EnergyPlus Weather (EPW) files using UK Climate Projections 2009 (UKCP09) data (Du et al. 2012; Mylona 2012; Tian and Wilde 2011), very few use the latest UKCP18 projections, limiting climate representation accuracy (Xie et al. 2025; Mourkos et al. 2024). These gaps hinder the development of integrated retrofit-adaptation strategies that optimise both energy performance and thermal comfort over building lifespans. Given the long timescales involved, simplified yet accurate BES approaches are valuable to efficiently assess whole-building impacts of retrofit and adaptation scenarios (Peinturier and Wallom 2025).

This study leverages simplified BES methods to investigate how future climate affects building energy performance and thermal comfort while evaluating NZC retrofit effectiveness and identifying when additional comfort measures are needed. The paper addresses gaps by generating Oxford-specific UKCP18 EPW weather files, implementing multi-year model calibration, and utilising PMV-based thermal comfort analysis. The framework is tested on three University of Oxford buildings, comparing energy and thermal comfort results between historical (2022-2024) and future (2025-2080) climate data across multiple scenarios: no retrofits, NZC retrofits, and climate-specific adaptation measures.

METHODOLOGY

This section outlines the methodology for this study. All building energy models are simulated using DesignBuilder, the graphical interface to EnergyPlus (EnergyPlus 2023). The baseline historical non-retrofitted models (H-NR scenario) were previously created and calibrated against 2023 real data in a study examining modelling simplification impacts on BES accuracy (Peinturier and Wallom 2025). Calibration is extended to 2022 and 2024 to enhance robustness and capture multi-year variations. Monthly energy consumption is quantified and thermal comfort assessed using PMV. NZC retrofit measures are then simulated over the 2022-2024 historical period (H-R scenario) to quantify energy reductions and verify comfort impacts under present climate conditions. The retrofitted models are subsequently simulated under future weather conditions across three time periods from 2025 to 2080 (F-R scenario) to investigate NZC retrofit impacts on future energy usage and thermal comfort, determining longevity of current designs and timing for additional interventions. Finally, where NZC retrofits compromise future comfort, additional climate adaptation measures are simulated to identify necessary supplementary measures and optimal implementation timeframes (F-ADP scenario). The methodology is applied across three non-domestic case study buildings of varying type and age from the University of Oxford.

Model Calibration and Historical No Retrofit Scenario

The H-NR models serve as baselines representing current building conditions. They use Actual Meteorological Year weather files from Oikolab, providing post-processed historical data in EPW format for BES (Oikolab 2023). Energy calibration is validated using coefficient of variation of root mean square error (CV(RMSE)) and normalised mean bias error (NMBE) on monthly data across 2022-2024, meeting ASHRAE Guideline 14-2014 standards with CV(RMSE) below 15% and NMBE between -5% and 5% (ASHRAE 2014). Thermal comfort is assessed using Fanger's PMV model, ranging from -3 (cold) to 3 (hot), simulated on DesignBuilder per zone and averaged monthly (DesignBuilder 2025). ASHRAE 55 recommends PMVs between -0.5 and 0.5, while ISO 7730 sets hard limits of -2 to 2 and recommends -0.7 to 0.7 for existing buildings (ISO 2005; ANSI and ASHRAE 2023).

Historical Net-Zero Carbon Retrofit Scenario

The H-R models incorporate combined NZC measures, whose individual energy impacts were previously assessed in the modelling simplifications study (Peinturier and Wallom 2025). The retrofits are summarised in Table 1. This combination ensures operational energy use and on-site renewable generation meet UK Net Zero Carbon Buildings Standard targets (Better Buildings Partnership et al. 2025). The H-R models are simulated for 2022-2024, with energy usage and PMVs compared against the H-NR scenario to assess NZC retrofit impacts on energy consumption and thermal comfort.

Table 1. Simulated Net-Zero Carbon Retrofits (Weerasinghe et al. 2024; UKGBC 2024; 2022)

Retrofit	Description
Systems/Control Maintenance	Equipment or control malfunction adjustments
HVAC* Setpoints and Schedules	Heating: 20 Oct to 01 May (7 am to 7 pm); Heating setpoints decreased by 1°C (34 °F)
Low Energy Lighting and Controls	Replace all lights with light-emitting diode (2.5 W/m^2 or 0.2 W/ft^2); Dimmable lights
Airtightness	Reduce air infiltration rate by 30%
Roof, Wall, and Floor Insulation	Reduce the roof, wall and floor U-values by an absolute 0.15, 0.10 and 0.08 W/m^2K (0.03, 0.02, 0.01 $Btu/h{\cdot}ft^2{\cdot}°F$) respectively
Window Replacement	Triple glazing: 4/12/4/12/4 mm (0.2/0.5/0.2/0.5/0.2 in) with argon
Heat Decarbonisation	Replace gas boilers with air source heat pumps - coefficient of performance of 3.5
Rooftop Photovoltaic	Install 200 W/m^2 (19 W/ft^2)-available roof area

**HVAC = heating, ventilation, and air conditioning*

Future Net-Zero Carbon Retrofit Scenario

The retrofit models are then simulated using future weather data (F-R scenario). Oxford-based UKCP18 EPW future weather files are created using 2025-2080 climate projections under the highest emission scenario (Representative Concentration Pathway 8.5 (RCP8.5)) for control ensemble member 01 (Met Office 2025), using methodologies adapted from previous studies (Mourkos et al. 2024; Xie et al. 2025). Table 2 summarises the variables and processing methods for generating the files. The 2025-2080 timeframe is divided into three periods following the IPCC Sixth Assessment Report warming thresholds: near-term (NT) (2021-2040), mid-term (MT) (2041-2060), and long-term (LT) (2061-2080) (IPCC 2023). For each period, two weather files are derived: Test Reference Year (TRY) and Design Summer Year (DSY) (CIBSE 2025). For each time period, the TRY provides the most representative months and the DSY represents the hottest summer year (Levermore and Parkinson 2006). Each F-R model is simulated across the three periods for both TRY and DSY conditions, with energy outputs and PMVs compared against H-R scenario results to assess future weather impacts on thermal comfort in NZC retrofitted buildings.

Table 2. Variables and Processing Methods Used for Future EPW Files Generation

Variable	Spatial Resolution	Time Resolution	Source	Processing Method
Dry Bulb Temperature, Precipitation, Wind Speed	2.2 km (1.4 mi)	Hourly	UKCP18	Directly used
Shortwave Radiation	25 km (16 mi)	Monthly	UKCP18	Delta anomaly applied to historical hourly global horizontal irradiance (GHI)
Cloud Cover, Sea Level Pressure, Humidity	2.2 km (1.4 mi)	Daily	UKCP18	Reshaped hourly from historical profile (2014-2024)
Direct Horizontal Irradiance, Direct Normal Irradiance	N/A	N/A	Derived	Derived from GHI
Dew Point Temperature, Relative Humidity	N/A	N/A	Derived	Derived from dry buld temperature, humidity, and pressure

Future Adaptation Scenario

Based on thermal comfort results from the F-R scenario, adaptation measures are applied to address potential overheating and restore acceptable thermal comfort thresholds when necessary (F-ADP scenario). The measures are summarised in Table 3. They are tested individually on retrofitted models using the LT DSY weather file, representing the most critical overheating scenario. The optimal combination is selected based on achieving reasonable PMVs while minimising energy use. This selected combination is then applied across all other future weather scenarios, with results compared against F-R models without adaptation measures to assess effectiveness in mitigating warming impacts on thermal comfort.

Table 3. Simulated Passive and Active Cooling Adaptation Measures (Gamero-Salinas et al. 2021; Schünemann et al. 2020; Shen et al. 2025; Oropeza-Perez and Østergaard 2018)

Measure	Description
Overnight Natural Ventilation (Passive) (N)	Automated overnight window opening based on temperature
External Shading Device (Passive) (E)	Combination of overhangs, side fins and louvred panels
External Reflective Coating on Windows (Passive) (C)	60% reduction of windows total solar transmission (e.g. semi-opaque film)
Automated Indoor Blinds (Passive) (B)	Automatic indoor blind rolling when solar irradiance > 120 W/m^2 (11 W/ft^2)
Improved Wall Absorptance (Passive) (W)	50% reduction in wall external layers solar absorptance (e.g. white paint)
Light-Reflective Roof Covering (Passive) (R)	50% reduction in roof external layers solar absorptance (e.g. green roof)
Mechanical Ventilation (Active) (M)	Installation of temperature-controlled air-handling units and fans in all zones
Air-Conditioning (Active) (AC)	Installation of variable refrigerant flow indoor units in all zones

Case Study Context

The methodology is tested on three case study buildings from the University of Oxford, which DesignBuilder models are depicted in Figure 1. The buildings vary in size, age, and type. AWB (2013) is a large higher education building (21,090 m² or 227,000 ft^2) containing offices and teaching spaces. It lacks active cooling and features a large window-to-wall ratio (WWR). PHARM (1989) is a medium-sized laboratory building (6,436 m² or 69,270 ft^2) with a small WWR, equipped with AC in most zones. HH is a small office building (1,124 m² or 12,100 ft^2) from the 1960s, refurbished in 2022. Metered energy data for all buildings (2022-2024) is obtained through the University's estates services online energy dashboard. Additional building details are available in the previous study on modelling simplications (Peinturier and Wallom 2025).

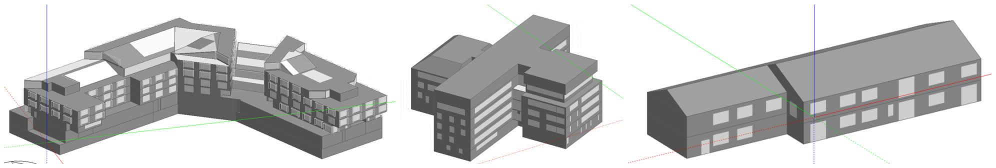

Figure 1 DesignBuilder models of the three case study buildings: AWB, PHARM, and HH (left to right).

RESULTS AND DISCUSSION

This section summarises findings from testing the proposed methodological framework on the three case study buildings. First, the generated historical and future weather data is presented. Monthly energy and PMV outputs are then analysed, compared, and discussed for the H-NR, H-R, F-R and F-ADP scenarios.

Historical and Future Weather Data Generation

The monthly daytime outdoor temperatures for 2022-2024 and generated TRY and DSY files for the NT, MT, and LT periods are depicted in Figure 2.

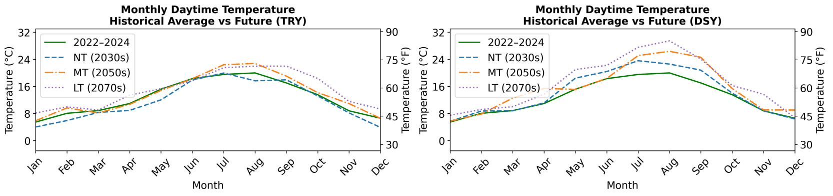

Figure 2 Monthly daytime temperatures (7 am–7 pm) for historical period (2022-2024) and future climate projections for TRY (left) and DSY (right) scenarios across NT, MT, and LT periods.

MT and LT TRY temperatures average 1°C (34°F) and 2°C (36°F) higher than 2022-2024 respectively. DSY temperatures average 2°C (36°F) higher than corresponding TRY values, with LT DSY summer temperatures reaching up to 7°C (45°F) above 2022-2024 averages. These substantial temperature increases, particularly during summer, raise significant concerns for indoor thermal comfort and highlight the need for additional cooling strategies.

Historical No Retrofit and Net-Zero Carbon Retrofit Scenarios

Figure 3 shows metered and simulated monthly electricity and gas consumption for each case study building under H-NR and H-R scenarios. Baseline H-NR model calibration meets ASHRAE Guideline 14 standards. H-R scenarios reduce monthly electricity use by 13% (AWB), 10% (HH), and 6% (PHARM). Gas consumption is eliminated through heating electrification, shifting AWB and HH electricity peaks from summer to winter, while PHARM retains summer peaks from AC operations. Average monthly PMVs are plotted against daytime outdoor temperatures for H-NR and H-R scenarios in Figure 3. Comfort sensitivity varies by building, with PMV increasing most rapidly with temperature in AWB, moderately in HH, and least in PHARM. Despite being newest, AWB shows highest PMVs, rising from near-neutral in winter to nearly 1.0 at 22°C (72°F), with NZC retrofits pushing maximum PMV to 1.58. Monthly comfort thresholds (PMV > 0.5) occur at approximately 15°C (59°F) for AWB, 19°C (66°F) for PHARM, and 21°C (70°F) for HH, highlighting AWB's summer vulnerability due to no active cooling and high WWR. PHARM displays different patterns, with a maximum average PMV of 0.73 at 12°C (54°F) in H-R scenarios while summer PMVs remain around 0.5 in both scenarios. The presence of AC in most of PHARM zones makes indoor temperatures largely independent of outdoor conditions, reducing differences between H-NR and H-R summer PMVs. Finally, HH shows near-neutral winter PMVs, with H-R averaging 0.2 lower than H-NR due to heating setpoint reduction from 22°C (72°F) to 21°C (70°F) to decrease heating demand while maintaining acceptable temperatures. Overall, H-R scenarios shift PMVs by approximately 0.27 across all buildings, with months exceeding a PMV of 0.5 increasing from 10% (H-NR) to 43% (H-R). While NZC retrofits successfully reduce winter heating demand through improved insulation, they simultaneously worsen summer thermal comfort conditions over the historical period due to increased overheating.

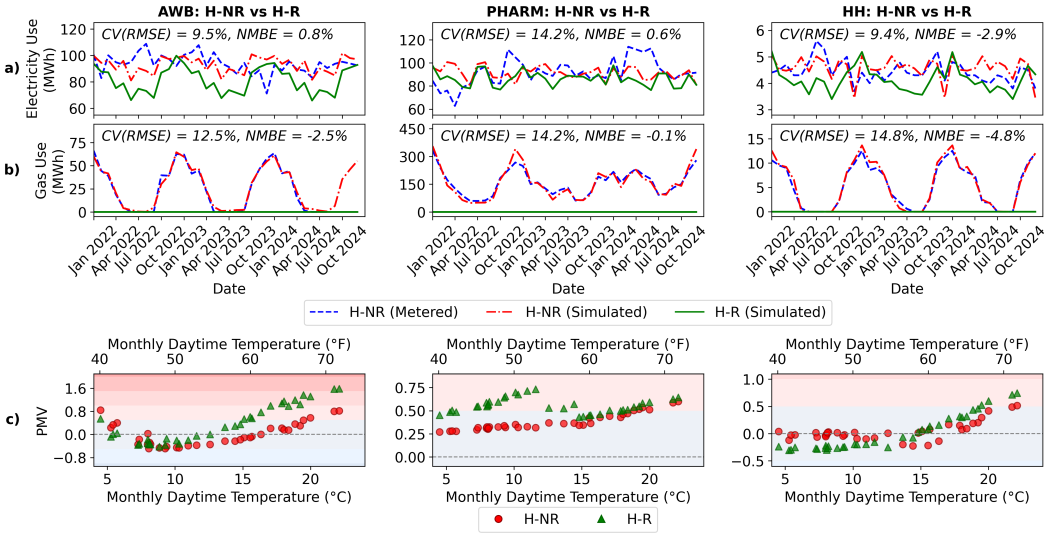

Figure 3 H-NR vs H-R: average monthly electricity use (a), gas use (b), and PMV (c) for each building.

Future Net-Zero Carbon Retrofit Scenario

The average monthly PMVs against daytime temperature and monthly electricity use for the F-R scenario are depicted in Figure 4. F-R PMV patterns follow similar trends to the H-R scenario but with upward shifts across all buildings. PMVs increase by 0.11 (NT TRY), 0.2 (MT TRY), and 0.27 (LT TRY) on average across buildings, with DSY scenarios showing additional 0.17 increases. All values exceed acceptable limits, especially AWB seeing monthly summer PMVs reach up to nearly 3.0. Additionally, LT-DSY scenarios show up 10-30% increases in electricity use during peak summer months relative to H-R. Absent further adaptation, retrofitted buildings will experience greater thermal discomfort and higher electricity use during the most critical future months, particularly as current NZC strategies prioritise fabric upgrades and added insulation.

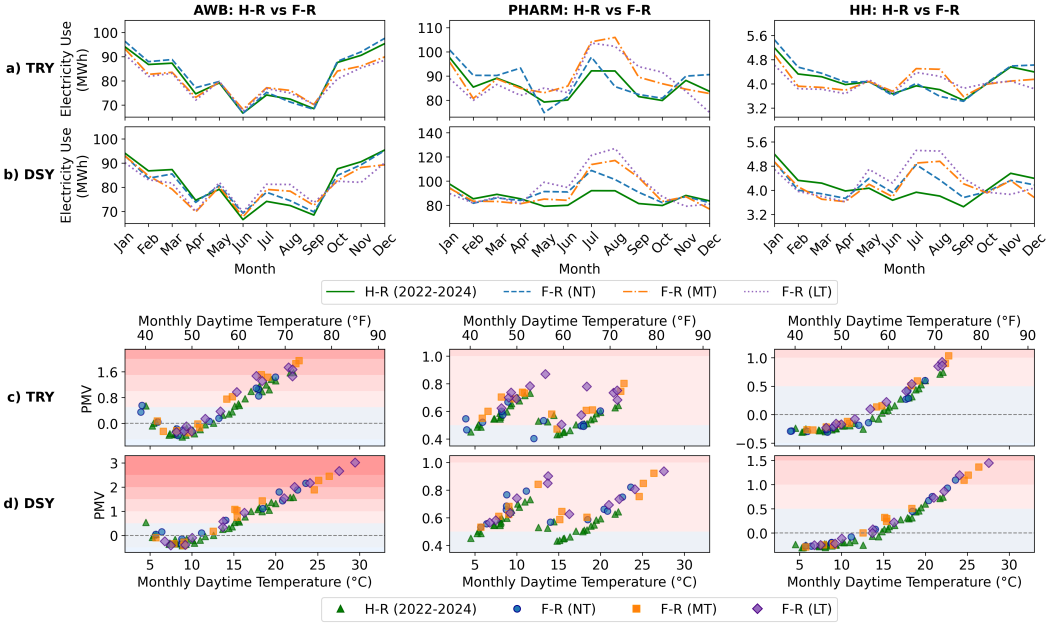

Figure 4 H-R vs F-R: average TRY (a, c) and DSY (b, d) monthly electricity use and PMV for each building.

Future Adaptation Scenario

With monthly PMVs well exceeding 1.0 in summer during the hottest LT period for retrofitted buildings, developing adaptation cooling measures to reduce PMV while mitigating electricity use is critical. BES can virtually test adaptation measures, providing lessons for future retrofit guidelines and ensuring NZC retrofits are climate-resilient. The average August PMVs and electricity use for each case study building under LT DSY conditions are shown in Figure 5 for different adaptation measure combinations (from Table 3). While achieving PMVs around 0.5 requires intensive AC use, reaching PMVs below 1.0 is possible with appropriate passive or hybrid measures. AWB achieves a PMV reduction from 3.01 to 0.93 through passive measures supplemented by mechanical ventilation, increasing monthly electricity use by 60%. PHARM's optimal trade-off reduces PMV from 1.09 to 0.75 for no electricity changes, using natural ventilation only as other shading measures increased lighting usage and internal gains. HH achieves fully passive optimisation, decreasing PMV from 1.79 to 0.97 while reducing electricity use by 23%.

The selected optimal combinations are then modelled across all other future scenarios with results shown in Figure 6. F-ADP scenarios reduce average TRY summer PMVs from 0.95 to 0.34 on average across the three buildings. AWB's PMV reduction requires 43.5% increased monthly electricity use due to mechanical ventilation, though still meeting UK Net Zero Carbon Buildings Standard targets. On the other hand, HH experiences 10% winter increase and 10% summer decrease in electricity use, redefining seasonal peak electricity demand patterns. Additionally, under DSY conditions, AWB and HH PMVs increase very linearly with temperature; passive adaptation primarily shifts the PMV-temperature curve downward rather than flattening its slope, meaning extreme-heat months might still require active operational strategies. Nevertheless, Figure 6 provides insights into the timeline for implementing secondary retrofit/adaptation measures, likely within the next 20-40 years depending on building type and design.

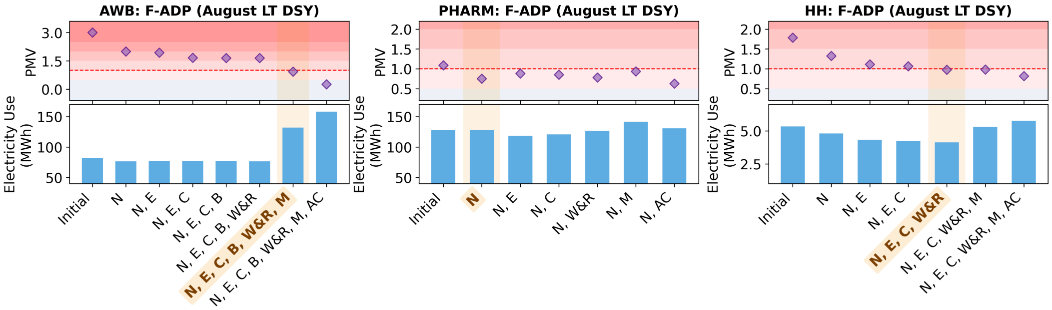

Figure 5 Adaptation measure selection: monthly PMV and electricity use trade-offs for August LT DSY.

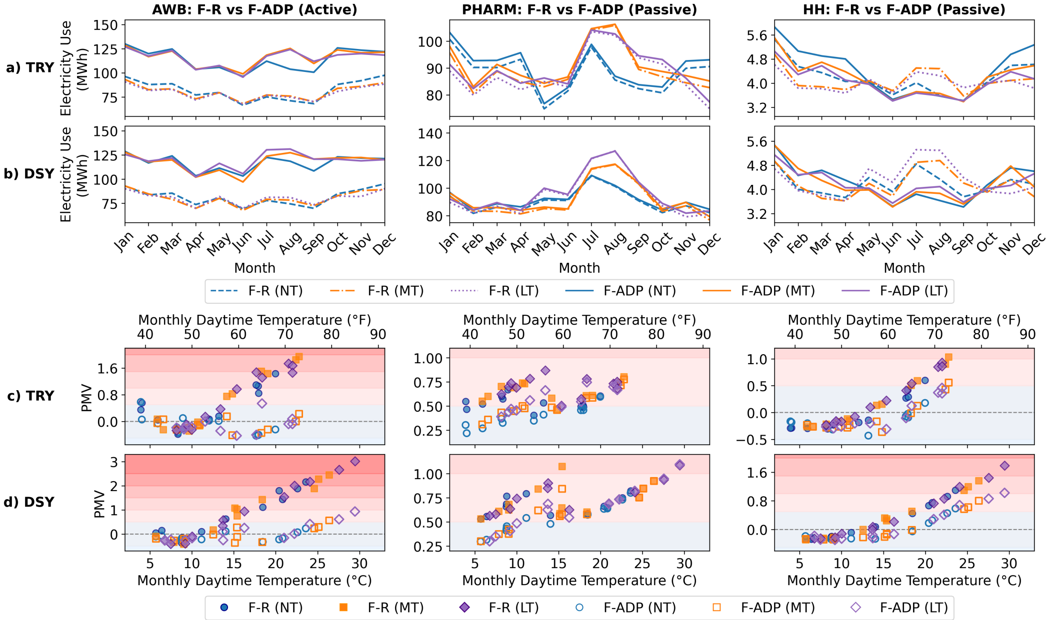

Figure 6 F-R vs F-ADP: average TRY (a, c) and DSY (b, d) monthly electricity use and PMV for each building.

CONCLUSION

This study addresses key challenges in enabling a net-zero built environment while ensuring building climate resilience by evaluating the long-term effectiveness of net-zero carbon (NZC) retrofits under future climate scenarios. Using building energy simulation on three University of Oxford case study buildings of varying type and age, energy use and thermal comfort are compared across four scenarios: historical non-retrofitted (H-NR), historical retrofitted (H-R), future retrofitted (F-R), and future adapted (F-ADP). Simulations are run using historical ERA5 weather data (2022-2024) and UKCP18 projections (2025-2080) across near-term, mid-term, and long-term periods under typical (TRY) and extreme summer conditions (DSY).

Results highlight that current retrofit practices, while achieving net-zero energy use, present thermal comfort challenges under future climate conditions, particularly during summer. While traditional NZC retrofits focus on enhanced insulation to reduce winter heating demand, they can simultaneously worsen summer thermal comfort, particularly in naturally ventilated buildings where PMVs reach unacceptable levels during extreme heat events. Months exceeding comfortable PMV thresholds increase from 10% (H-NR) to 43% (H-R), with further deterioration under future weather. Importantly, building age and typology significantly influence climate resilience, with newer buildings not necessarily outperforming older ones. The F-ADP scenario results reveal that achieving acceptable future thermal comfort requires strategic combinations of passive and/or active measures depending on building characteristics. While fully passive strategies can reduce PMVs below 1.0 in some cases, some buildings may still require active cooling, highlighting the need for hybrid-readiness planning.

This work provides a replicable framework for evaluating NZC retrofit longevity and informing climate-adaptive building strategies. As most UK buildings expected to remain operational through 2050 undergo rapid NZC retrofits to meet climate targets, ensuring these interventions are climate-resilient is essential for long-term building stock performance. Future works will include running simulations across additional climate scenarios to quantify result uncertainties and perform an attribution study to better understand the correlations between temperature changes, energy use, and thermal comfort based on buildings characteristics. Additionally, integrated NZC retrofit-adaptation strategies will be further investigated and simulated to develop a framework that ensures future building interventions simultaneously achieve net-zero performance and climate resilience, avoiding counterproductive measures that require subsequent correction.

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NOMENCLATURE

AC = air conditioning
AWB = Andrew Wiles Building (case study building)
BES = building energy simulation
CV(RMSE) = coefficient of variation of root mean square error
DSY = design summer year
EPW = EnergyPlus weather file format
F-ADP = future adaptation scenario
F-R = future net-zero carbon retrofit scenario
GHI = global horizontal irradiance
HH = Holywell House (case study building)
H-NR = historical no retrofit scenario
H-R = historical net-zero carbon retrofit scenario
HVAC = heating, ventilation, and air conditioning
LT = long-term period (2061-2080)
MT = mid-term period (2041-2060)
NMBE = normalised mean bias error
NT = near-term period (2021-2040)
NZC = net-zero carbon
PHARM = Pharmacology Building (case study building)
PMV = predicted mean vote
RCP = Representative Concentration Pathway
TRY = test reference year
UKCP09, UKCP18 = UK Climate Projections 2009 and 2018
WWR = window-to-wall ratio

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