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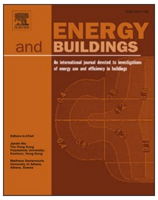

Prospect of energy conservation measures (ECMs) in buildings subject to climate change: A systematic review

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ABSTRACT

Energy conservation measures (ECMs) are often chosen for their immediate benefits, such as suitability to past/current climate conditions and rapid economic returns. However, the longevity of these ECMs poses a risk of becoming outdated or ineffective as climate change alters the very climatic parameters they were designed for. This paper provides insight into the foresight required when selecting an ECM, focusing on its long-term viability under global warming. The ECMs discussed encompass passive strategies such as building envelope insulation and window design, active systems like efficient HVAC and heat pumps, and renewable systems. The need for context-specific ECM selection tailored to local climate, building type, and cost-effectiveness is highlighted. Major challenges and barriers influencing the widespread adoption of ECMs under global warming are addressed, including: 1) considering long-term effectiveness in ECM decision-making, as measures effective initially may become disadvantageous in the future, and vice versa; 2) adopting a life cycle perspective considering both embodied and operational impacts; 3) developing robust, resilient building designs under climate change uncertainty; and 4) potential strategy shifts, such as transitioning from passive cooling techniques to active cooling systems. Meanwhile, policy interventions through regular updates to building codes and standards are needed to keep pace with evolving climate conditions and engage diverse stakeholders to balance multiple objectives, including environmental, societal, and human factors. Incorporating climate change into decision-making for ECM implementation is paramount for building energy adaptation to a warming climate.

1. Introduction

Climate change poses a significant health threat to humanity [1,2], driven primarily by human activities that increase atmospheric greenhouse gas (GHG) concentrations. The building sector is a major contributor to this crisis, accounting for 37 % of global GHG emissions in 2021 [3]. In the U.S. and EU [4,5], buildings are responsible for about 40 % of overall energy consumption, with even higher figures reported in developing economies like China [6]. With population growth and urbanization, the demand for energy in buildings will continue to rise, further exacerbating global warming [7].

The relationship between the building sector and climate change is complex and intertwined. Buildings contribute to GHG emissions through embodied emissions from materials and operational emissions [8]. Global warming, in turn, leads to increased average temperatures and extreme weather events that influence building energy loads and building structures [9], as well as jeopardize the health of occupants. Global warming is expected to alter building energy demands significantly, with higher average temperatures likely reducing heating needs while increasing cooling loads [10]. This shift underscores the importance of a balanced approach to heating and cooling strategies in future building designs. This relationship affects all types of buildings, including residential, commercial, and industrial buildings, each with its unique challenges and opportunities for mitigation and adaptation. In

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Abbreviations: ECM, Energy conservation measure; GHG, Greenhouse gas; UHI, Urban heat island; HVAC, Heating, ventilation, and air conditioning; LCA, Life cycle assessment; IHG, Internal heat gain; SHGC, Solar heat gain coefficient; WWR, Window-to-wall ratio; PCM, Phase change material; nZEB, Nearly zero energy building; PV, Photovoltaic; RCP, Representative concentration pathway; SSP, Shared socioeconomic pathway; A/C, Air conditioning; ASHRAE, American Society of Heating, Refrigerating and Air-Conditioning Engineers.

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addition, the microclimate shaped by the built environment significantly influences the energy demands of local buildings, while climate change exacerbates the urban heat island (UHI) effect [11]. As global warming becomes more severe and evident, reducing the environmental impact of buildings becomes essential.

A search of the Web of Science database on the impact of climate change on building energy reveals an increasing upward trend in publications. This surge in research is particularly noteworthy given that the building industry is currently not on track to meet climate goals. Previous studies (Table A.1) providing insights into the implications of climate change on building energy have been conducted at an early stage [12] and have focused on specific locations [11,13], different building types [14], climate zones [15], and quantitative analysis [16]. For example, Abolhassani et al. [15] discussed heating and cooling energy under global warming based on ASHRAE climate zones in 2023. Campagna and Fiorito [16] reviewed the impact of climate change on building energy from a quantitative perspective.

The increase in both average and peak temperatures, along with more frequent extreme weather events, will lead to challenges for heating, ventilation, and air conditioning (HVAC) systems, potentially resulting in insufficient heating and cooling capacities. This will strain the grid and raise the risk of power outages when HVAC systems are operating at full capacity [17]. Given the challenges posed by climate change to building energy systems, it's essential to explore strategies for reducing energy consumption and enhancing building resilience.

Implementing energy conservation measures (ECMs) is a key strategy to reduce building environmental impacts. Costa et al. [18] defined ECMs as any technological resource used to reduce building energy consumption. The term is utilized in [19–21] and is also sometimes referred to as energy-efficiency measures [22,23], energy-saving measures, and energy retrofitting measures [24] with a different emphasis. ECMs in current weather conditions have been widely studied [23,25–27]. In addition, it is important to recognize that ECMs do not come without costs and trade-offs. Improved insulation, efficient HVAC systems, and other measures often require additional materials and resources, which can increase embodied emissions and costs.

While reviews exist on climate change adaptation measures, many focus on specific regions or were conducted when this field of study was still emerging [9,11,13]. Azimi Fereidani et al. [11] provided an overview of passive and active technologies in the Middle East, with a focus on building and urban scales. In the 2012 review [13], mitigation measures and adaptation were briefly discussed. Andrić et al. [9] discussed renovation measures across developed and developing countries and reported that these measures could reduce energy consumption by 38 % under future climate conditions. However, there remains a need for comprehensive, up-to-date reviews that provide a systematic overview of ECM under global warming across various regions and building types.

This review paper aims to present a holistic, global overview of ECMs for mitigating building energy consumption and associated GHG emissions in response to climate change. The analysis covers both residential and commercial buildings across various climate zones. The paper focuses on technical challenges, as well as the uncertainties related to climate projections and their impact on the effectiveness of ECMs. Specifically, the review aims to address: 1) What current and potential ECMs are discussed, and how might their effectiveness evolve? 2) What are the key technical, economic, and policy challenges facing the widespread adoption of ECMs in buildings, and how can they be addressed?

2. Methods

Scopus and Web of Science, two widely used databases, were utilized to identify relevant articles on the topics discussed. The search employed the following keywords and search terms: ("energy use" OR "energy performance" OR "energy consumption" OR "energy demand") AND ("climate change" OR "global warming") AND ("impact" OR "effect") AND ("building"). A total of 5745 returns were obtained, with 2788 from the Web of Science and 2957 from Scopus. The research was limited to peer-reviewed journal papers published in English. After removing duplicate publications, 2979 remained. Following screening of titles, abstracts, and keywords, only 386 articles were left for full-text screening.

Inclusion criteria were established to refine the selection of ECM studies contributing to climate change mitigation from the extensive list of retrieved articles. These criteria included that the focus of the article must be on technical ECMs under global warming. The article must involve the alteration of parameters related to building energy, and the full text of the paper must be accessible for screening. For instance, studies solely examining global warming potential in life cycle assessment (LCA) studies that included all the above keywords but did not involve the influence of global warming on building energy were excluded. ECMs that are widely discussed under current weather conditions but not in future conditions, such as dynamic façades, are not included in this study. Moreover, the uncertainty of parameters and optimization considerations were considered and incorporated into ECMs. In the end, a total of 128 articles were identified for discussion (see details in Section 3).

3. Energy conservation measure (ECM)

In this review, these ECMs can be categorized into the following groups: passive, active, and renewable technologies (Table 1).

3.1. Passive measures

Passive measures are ECMs that operate without requiring a power or mechanical system [26]. Properly designed buildings serve as the first line of defense against global warming by mitigating heat gain during summers and minimizing heat loss during winters [17]. These passive ECMs include: 1) thermal insulation of the building envelope, 2) implementing solar reflective materials, 3) green envelopes, 4) shading, 5) thermal mass and phase change material (PCM), 6) ventilation, 7) window design, 8) building design-related measures such as orientation and window-to-wall ratio (WWR), and 9) airtightness. Occupant behavior is also discussed in the passive measures. For instance, Pajek et al. [40] performed a multiple linear regression analysis to identify the most relevant passive ECMs in single-family detached buildings. The findings highlighted the evolving significance of passive ECMs in response to climate change. Notably, the opaque envelope's U-value emerged as the foremost determinant for heating loads. In contrast, the window-to-floor ratio was identified as pivotal for cooling loads across both present and future scenarios. Zou et al. [94] conducted a sensitivity analysis of four passive ECMs under representative concentration pathway (RCP) scenarios.

3.1.1. Thermal insulation of the building envelope

Enhancing envelope insulation emerges as the most widely favored ECM for addressing climate change, as the building envelope serves as the first defense against the external environment. For instance, Radhi [45] showed that improved insulation could reduce cooling energy consumption by 15.5–19.9 % in different climate scenarios. However, the effectiveness of insulation can vary significantly depending on the studied climate, future scenarios, and HVAC settings, often yielding contradictory results [39,75].

Pajek et al. [39] found that reducing the envelope U-value was the most effective ECM, although its energy-saving potential decreased as the climate warmed. This effectiveness was partly attributed to Montenegro's current status as one of the least energy-efficient nations in Europe, with generally poor existing thermal insulation. In contrast, Waddicor et al. [75] reported that upgrading wall insulation had no significant impact on energy performance in their study location, where

Table 1

An overview of the building ECM to mitigate the effect of global warming on building energy consumption.

ECMs	Details	References
Passive measures		
Thermal insulation of the building envelope (U-value)	Thickness of insulation of walls, roofs, and floors	[19,22,24,28–112]
Thermal mass and phase change materials	Increasing thermal mass	[40,45,51,53,59,64,79,80,102,105,113–118]
Airtightness/Infiltration rate		[19,28,35,46,48,52,54,55,59,65,83,88,96,97,102,107,108,112]
Shading devices	Blinds, overhangs, awnings, curtains, and shading angle	[19,29,35,38,45–47,51,54,59–61,63–65,70,71,73,79,80,87–90,96,102,105,119–125]
Windows design	U-Value	[19,22,24,28,31–35,37,39–41,44–49,52,53,55,59,60,65,68–71,74,75,77–80,83,87–90,92,95–100,102,103,105,106,108,109,112,121,123,124,126]
	Solar Heat Gain Coefficient (SHGC)	[19,24,28,29,31–35,39,40,44–49,51,54,55,59,68,69,75,81,87–90,94,97,100,102,103,105,106,108,109,112,120,121]
Building design related	window-to-wall ratio, window-to-floor ratio, and window size	[28,31,32,35,40,45,52,53,60,61,65,67,80,81,87,94,102,105,107,121,123,124,127]
	Orientation, shape coefficient, Building geometry generation	[37,40,51–54,60–63,87,95,105,107,121,125,127–129]
Natural ventilation/night cooling/night ventilation		[19,38–40,46,51–54,61–65,70,71,85,90,96,115,118,119,123–126,128,130–136]
Implementing solar reflective materials	silver roofs, cool roofs, cool walls	[29,36,39,40,43,44,51,53–55,59,61–64,66,70,73,79,87,102,120]
Green envelopes	green roof, garden roof, green façade	[43,63,64,89,91,99,133,137,138]
Occupant behavior	Adjusting Setpoints	[19,21,24,31–34,46,54–56,71,75,78,82,85,99,121,123,124,134–136,139–142]
	Occupancy, HVAC schedules, patterns, and working hours	[54,82,85,100,123,124,135,136,142–144]
Active systems		
HVAC Systems		[28,49,57,111,113,131,139,145–149]
Internal heat gain (IHG)	Energy-efficient level of lighting	[19,22,24,28,30–32,38,46,48,52,54,70,71,75,81,83,88,118,121,123,124,131,150,151]
	Energy-efficient level of appliances	[22,24,30,48,52,54,70,71,81,83,88,118,121,124,131,150,151]
Efficient chiller	Coefficient of Performance and Energy Efficiency Ratio	[19,28,31,32,48,54,75,98,128,139]
Efficient boiler		[19,28,48,50,83,98,139]
Heat recovery systems		[22,24,38,65,90,121]
Mechanical ventilation	Fan efficiency, ceiling fans, portable fans	[22,28,38,65,121,122,126,132,139,140]
Renewables systems		
Renewable energy production	photovoltaics systems, solar thermal systems, geothermal energy, and wind turbines.	[38,49,50,52,57,130,131,139,145,147,148]

Note:

Only studies that changed parameters are listed. For example, if the study involves photovoltaics but does not change parameters, it is not listed in the Table.

In instances where certain aspects are less emphasized, such as the reduction of thermal bridges in buildings, shading setpoints and people's metabolism, their presence may not always be so common and is consequently excluded from the list.

If windows are being considered for replacement, both the U-value and SHGC are considered to have changed.

Different building standards and optimization parameters are also listed here.

buildings already had 10 cm of insulation. These contrasting findings highlight several key factors that influence ECM effectiveness: 1) regional climate characteristics, where the balance between heating and cooling demands affects the impact of insulation improvements; 2) existing building standards, as regions with poor current insulation standards tend to benefit more from insulation upgrades; and 3) baseline conditions, where the effectiveness of insulation retrofits depends on the current insulation levels of the buildings. Insulation retrofits will still be effective for buildings that have poor insulation or were built before thermal regulations were implemented.

Studies by Rodrigues et al. [37,95] have shown that the ideal U-value or thermal transmittance for the future depends on the specific climate conditions. In regions where heating energy demand ranges from low to high, the ideal thermal transmittance may be higher or lower than the current value. The increased ideal thermal transmittance can be attributed to the intricate interplay between outdoor temperature and the building's capacity to dissipate heat. As the average temperature increases in this region, the outdoor temperature may fall within the setpoints of indoor comfort levels. Thus, the internal heat gain (IHG) will worsen the indoor thermal performance and require more heat release. Therefore, higher thermal transmittance in the envelope is preferred. On the other hand, in areas with already high cooling demand [37], a lower optimized thermal transmittance may be better. These regions exhibit average temperatures surpassing cooling thermostat thresholds in both present and projected climates, with minimal daily temperatures hovering near or above heating thermostats. In such circumstances, achieving lower appropriate thermal transmittance is desirable to minimize heat gains from the building envelope. Reflecting the trajectory in Singapore, the predominant approach to enhancing the thermal performance of future residential buildings is to bolster the envelope thermal insulation [105]. The optimal thermal transmittance in cooling regimes is influenced by the diurnal temperature swing outdoors relative to the interior cooling setpoint, as well as climate severity and cooling degree days. This relationship varies considerably by climate and is likely to change as climate change elevates nighttime temperatures. Furthermore, the optimal thermal transmittance can vary significantly for different building components, particularly for roofs and ceilings, which are more exposed to solar radiation.

While enhanced insulation has yielded favorable results in reducing heating energy requirements, it has also heightened the risk of overheating and increased cooling energy requirements. Jafarpur and Berardi [34] demonstrated that increasing the insulation and windows with triple glazing in office buildings was detrimental in the hot summer period, leading to a substantial rise in cooling energy demand, outweighing modest winter energy savings under a future climate, such as in Vancouver. However, in Quebec, retrofitting resulted in an energy reduction due to the larger decrease in heating load. Therefore, increasing insulation may be more reasonable in regions with colder climates, especially considering climate change. Studies [31,56,75] reported that adding insulation to the envelope would not be very effective in future climate scenarios. Improved insulation and airtightness of buildings can reduce heating energy demand during cold events. However, they may also cause overheating during extreme hot events if effective ventilation is lacking [17]. This underscores the importance of coupling enhanced insulation with effective passive cooling strategies such as natural ventilation, night cooling, and shading devices. When these well-insulated buildings are further integrated with optimal building control strategies to optimize year-round performance, they can achieve improved energy performance and thermal comfort.

3.1.2. Implementing solar reflective materials

As the demand for cooling increases in the future, the role of external opaque surfaces becomes more critical [40]. A strategy to reduce the cooling load of buildings is to employ solar reflective materials in the building envelope to help maintain a cooler surface temperature than conventional building envelopes (e.g., cool roofs). Karimpour et al. [44] have observed a growing preference for highly reflective roofs in the future to help mitigate increased cooling needs. In contrast, absorbent roofs are preferred in the current climate of Adelaide. Bamdad [36] indicated that in tropical and subtropical climates, cool roofs could potentially reduce energy usage by up to 14 % and 22 %, respectively, under current and future weather scenarios. Conversely, in regions with cool and mild temperate climates, this ECM initially led to a rise in total energy loads (heating penalty in cold months) under current conditions. However, this trend would shift towards energy savings in future timeframes for cities such as Canberra and Melbourne. This is in line with Virk et al. [43], who explored the microclimatic effects of cool and green roofs in an office building, both of which resulted in energy savings in 2050 scenarios. Cool roofs led to an annual energy penalty in the current weather in London due to winter performance, but they would lead to decreased energy in 2050. The study also highlighted that cool roofs were more effective in mitigating summer overheating compared to green roofs. Hosseini et al. [66] explored the energy performance of roof designs under global warming in the cold climate of Montreal, indicating that roofs with higher solar reflectance can reduce cooling energy and variance, thereby enhancing the robustness of the design. Therefore, choosing materials with low solar absorptance may be a key energy conservation strategy in building design, especially for hot climates and areas affected by the UHI effect.

3.1.3. Green envelopes

Green building envelopes, such as green roofs and green façades, serve as ECMs by incorporating vegetation to reduce heat transfer into the building's structure and promote evaporative cooling on the envelope's surface, which can also mitigate the UHI and improve air quality.

Roshan et al. [138] found that adopting a green wall resulted in a greater annual decrease in energy demand and GHG emissions in comparison to the green roof strategy and base case. Chan and Chow [137] revealed that the green roof maintained air conditioning (A/C) energy consumption at levels no higher than the current level in Hong Kong during the periods of 2011–2030 and 2046–2065, with reductions ranging from 2.4 % to 10 %. Qatar achieves annual energy savings of 2–4 % with green roofs and walls in 2020, 2050 and 2080 [99].

The implementation of green roofs resulted in greater energy savings in summer (~50 %) compared to values in winter (~20 %) for Esch-sur-Alzette in Luxembourg [91]. Virk et al. [43] found that the retrofitted green roofs had the potential to lower heating and cooling energy consumption while also mitigating overheating in naturally ventilated buildings. However, efficiency in summer is limited by proper irrigation, which enhances the dissipation of latent heat from the surface. As highlighted by Yang et al. [152], certain regions in Europe, like Athens, are anticipated to experience peak temperatures surpassing 40 ℃ more frequently. Hence, the feasibility of green envelopes in extreme climates needs concerns, given that the majority of plants thrive in the range of 0–40 ℃.

3.1.4. Shading

Using sun shading devices will become important to curb solar heat gains from windows and reduce the cooling load in future weather conditions [105]. Huang and Hwang [47] revealed that applying a shading device neutralized the increased cooling energy by 65.5 %, 37.5 %, and 27.7 % in the 2020 s, 2050 s, and 2080 s, respectively, in Taiwan. According to Dodoo and Gustavsson [122], shading was the most effective single measure in Sweden. Silva et al. [119] reported that night ventilation could reduce the peak cooling energy by 3.5–10.9 %, and with shading, it could be reduced by 46.4–62.7 %. For four residential building typologies [79], louvered shading proved to be the most effective way to reduce overheating hours compared to external insulation, high albedo and exposed mass.

Ouedraogo et al. [80] reported that external shading was more effective than curtains or balconies, resulting in cooling reductions of up to 40 %, 32 %, and 15 % across various periods. This is because external shading blocks solar radiation from entering the building, and the absorbed radiation is reflected and conveyed back into the outdoor environment. However, it's essential to note that this study was conducted in Burkina Faso, West Africa, which has a tropical climate with high average temperatures, thus emphasizing cooling rather than heating concerns, especially in light of global warming. As the climate changes, both cooling and heating energy demands will be impacted by shading solutions. Gupta and Gregg [79] further emphasized the significance of occupant behavior in optimizing the effectiveness of shading systems. Occupant-controlled shading systems can minimize overheating while maximizing solar radiation for heating compared to fixed shading systems. Another consideration is the potential increase in lighting electricity demand when implementing shading solutions, as noted by Ouedraogo et al. [80].

In addition to shading devices directly attached to or integrated into buildings, urban-green elements, including trees, grassland, parks, and water bodies, may be a solution and are regarded as cost-effective, environmentally friendly, and politically acceptable [153]. Urban blue-green elements can provide localized shading and cooling benefits to nearby buildings, thereby helping to alleviate the UHI effect and mitigate average temperature increases caused by climate change. However, their effectiveness depends on various factors, such as the size and density of vegetation, seasonal and diurnal differences, and the specific climate and latitude.

3.1.5. *Thermal mass and PCM*

Thermal mass refers to the capacity of a material to absorb, store, and release heat to stabilize the daily indoor temperature. Materials such as concrete, stone and water have a high thermal mass. They are capable of absorbing heat during warmer daytime conditions and releasing it slowly at night in cooler periods, thus decreasing the higher temperature swings. Wang and Chen [154] advocated for integrating thermal mass into building design, particularly for buildings relying on natural ventilation, to stabilize the temperature and provide a buffer against extreme weather events. Hong et al. [17] affirmed the effectiveness of thermal mass in addressing short extreme heat events (1 or 2 days).

Studies have indicated potential energy savings associated with high thermal mass, with Radhi [45] showing a 14.8 % electricity saving in the future scenario. However, Gupta and Gregg [79] warned that thermal mass ECM is complex, highlighting the risk of increased heating energy and overheating time if misplaced. Ouedraogo et al. [80] further emphasized that a 50 % increase in thermal mass led to a 3 % increase in cooling load during three time periods in West Africa. This is attributed to the relatively limited natural ventilation and the slow process of heat release during the night, which maintains higher temperatures at night and leads to increased cooling requirements the next day. Consequently, effective implementation of thermal mass as an ECM necessitates user interaction (natural ventilation).

PCM works by changing its phase from solid to liquid (or vice versa) at a phase change temperature to absorb (or release) heat. The incorporation of PCMs into the building envelope represents a burgeoning area of interest for diminishing cooling requirements and addressing overheating risk, particularly in lightweight structures with low thermal inertia. Nurlybekova et al. [116] examined the energy efficiency of buildings incorporating PCM across various cities in the Köppen climate classification Cwa zone. Gassar and Yun [117] examined the application of PCMs in buildings located in East Asia to anticipate their effectiveness under future climate scenarios. Kharbouch [114] demonstrated a significant reduction of cooling loads in Moroccan office buildings through PCM integration over the 30-year lifespan, with a reduction of 9.87 % and 20.5 % for free-running and air-conditioned buildings, respectively.

Choosing the appropriate PCM melting temperature is critical for optimizing energy efficiency, and temperatures vary by climate and HVAC system. The efficiency of the ideal PCM slightly diminishes as average temperatures rise. Kharbouch [114] identified optimal melting temperatures for free-running (28 ℃) and air-conditioned (26 ℃) buildings. An interesting finding is that for free-running buildings, the optimum melting temperature would slightly increase from 28 °C in the 2020 s and 2030 s to 29 °C in the 2040 s due to the outdoor temperature increase. From a life cycle perspective, a melting temperature of 28 °C was considered to perform the best.

Additionally, the combination of PCMs with night ventilation strategies can further enhance their effectiveness in the heat discharge process. Khawaja and Memon [115] supported that the integration of PCM with night ventilation and changeover ventilation mechanisms led to cooling energy savings of up to 35 % and 96 %, respectively. PCM with night ventilation is preferable in climates (Cwa, Cfb, Dfa and Dfb) characterized by significant diurnal temperature fluctuations.

3.1.6. *Ventilation*

Adequate ventilation stands as a key strategy by providing fresh air, reducing cooling demand, and maintaining thermal comfort. Various ventilation strategies, including natural ventilation, mechanical ventilation, or a combination of both, are employed to achieve these objectives. Natural ventilation depends on openings such as windows or doors to create an airflow induced by wind or the stack effect. Night cooling aims to remove excess heat and lower temperatures at night through natural ventilation [9]. Mechanical ventilation employs devices such as fans or ducts to control the airflow.

Studies have underscored the significance of natural ventilation in mitigating cooling demands across different climatic regions. Pajek et al. [39] identified natural ventilation as an effective ECM, followed by insulation and shading setpoints. Barea et al. [128] also supported that natural ventilation was essential in all scenarios, leading to up to 72 % cooling savings in Argentina's arid climate with high irradiance. However, the effectiveness of natural ventilation may diminish under higher future average temperatures, as suggested by Heracleous et al. [90], with day and night ventilation leading to 62 %, 56.3 %, and 52.9 % reductions in cooling demand at baseline, 2050 s, and 2090 s, respectively. Nonetheless, it remains a crucial strategy for mitigating heat gains. Silva et al. [119] found that night ventilation could reduce national cooling energy by 38 %. When combined with shading, this approach could achieve a maximum reduction of 84 % in future climates.

In Australia, the potential for energy savings through natural ventilation remains relatively consistent in cities with temperate and mild climates, such as Perth (~33 %), Sydney (~36 %), and Melbourne (~26 %) [132]. However, in Hobart, where the climate is colder and more humid, the energy savings from natural ventilation are projected to increase from ~ 23 % currently to ~ 32 % by the 2080 A1FI scenario. Conversely, in hot and humid climates like Darwin and Brisbane, the energy-saving potential of natural ventilation diminishes in the face of increasing cooling demands, dropping from ~ 23 % to ~ 10 % in Darwin and from ~ 47 % to ~ 33 % in Brisbane from the current scenario to the 2080 A1FI scenario. Therefore, these cities may need to supplement natural ventilation with cooling systems to ensure indoor comfort.

The success of natural ventilation interventions hinges significantly on behavioral aspects, patterns of building utilization, building automation and climate. Education and information about mean and peak temperatures and solar radiation intensity should be provided, as natural ventilation could have adverse effects if outdoor temperatures surpass indoor ones. Automated systems can help by controlling when and how natural ventilation is utilized, but their effectiveness will be limited in extreme heat conditions. Furthermore, nighttime temperatures are expected to rise significantly under global warming. This trend may lead to the loss of natural ventilation as a viable cooling strategy in warmer climates, such as the Mediterranean. D'Agostino et al. [120] have reported that the rising summer nighttime temperatures limit the effectiveness of natural or mechanical ventilation strategies. In scenarios where nighttime outdoor temperatures consistently exceed thermal comfort thresholds, occupant behavior becomes less relevant, and even automated controls may not provide sufficient cooling. Therefore, future building designs must consider the potential shift from passive cooling to active cooling strategies to adapt to these conditions.

For mechanical ventilation, mixed-mode ventilation combined with ceiling fan strategies has been identified as a viable option for achieving moderate to significant energy savings across Australian cities [132]. The study reported substantial energy savings with mixed-mode and ceiling fan, reaching up to 52.3 % in Brisbane under current climate conditions and up to 46.79 % under the A1FI scenario in 2080. In addition, Ferdyn-Grygierek et al. [111] suggested a hybrid cooling strategy, with mechanical cooling only operating when ventilative cooling could not provide comfortable conditions. In this way, the cooling system could use ventilation as a low-cost and environmentally friendly option as much as possible.

3.1.7. *Window design*

Window design parameters rank second among the most popular ECMs and play a crucial role in facilitating heat and sunlight exchange in buildings.

In a study for a humid and hot climate [59], researchers identified the solar heat gain coefficient (SHGC) as the most influential design parameter. Similarly, in the sensitivity analysis of parameters in Hong Kong, Liu et al. [102] stated that the SHGC was the most significant design parameter, followed by wall solar absorptance and shading overhang projection factor. In addition, the study indicated that window SHGC was instrumental in building energy efficiency and resilience to global warming [55]. In Sweden, combining energy-efficient windows with improved envelope insulation was the most effective retrofitting measure to reduce heating requirements [24].

However, the selection of window design should be tailored to specific locations and weather conditions. While low U-values in windows appear advantageous across diverse climates, the SHGC exhibits complexity and depends on climate, latitude, and solar exposure [75]. Notably, a low G-value for glass proves beneficial in warm climates like Hong Kong, Taiwan, and the UAE [45], where cooling demands predominate and little to no heating is required. Huang and Hwang [47] stated that lowering the SHGC neutralized 55.5 %, 32.3 %, and 23.5 % of additional cooling energy demands attributed to global warming in the 2020 s, 2050 s, and 2080 s, respectively, while enhancing the U-value of windows had a negligible impact on cooling energy in Taiwan’s hot and humid climate. Conversely, in higher latitudes where solar gains are desirable in the winter months, the preference for SHGC may differ. Shen et al. [19] reported that in office building retrofitting, higher U-values and higher SHGC are preferred in San Francisco. In comparison, lower U-values and SHGC are preferred in office building renovations in Philadelphia, where more outdoor climate insulation is required for buildings.

3.1.8. *Building design-related measures*

ECMs related to building design in the context of global warming primarily concentrate on parameters such as orientation, shapes, and WWR. These considerations are usually prioritized in the early design stage to effectively mitigate the effects of global warming. For instance, Taleghani et al. [129] noted that incorporating courtyards could reduce summer discomfort hours while increasing heating demand. The generative algorithm for creating randomized geometries on a two-story family house was evaluated for energy under global warming using EnergyPlus [37,95].

Guan [81] highlighted the significant influence of reducing the WWR on building thermal performance, with a decrease from 0.5 to 0.2, resulting in substantial energy savings (2.74–11.4 kWh/m^2/year) and reduced overheating hours (3.9–17.6 %) in the high emissions scenario projected for 2070. This finding aligns with recommendations from Liu et al. [35], who consistently advocated for a modest WWR of 0.2 and the use of horizontal shading panels as effective retrofitting measures across all climatic scenarios in Hong Kong. Rubio-Bellido et al. [127] further underscored the significance of considering location-specific design strategies and observing varying trends in WWR optimization over time in different climate zones in Chile. In addition, smaller windows with shading would help to decrease cooling and avoid direct sun or glare but may result in a lighting energy penalty.

Studies [63,87] have highlighted the implications of climatic changes on optimizing building orientations. Vasaturo et al. [63] showed that the south-facing building was the most favorable, and the north-facing building was considered the least favorable choice (maximizing heating). For the optimal cases of the classroom in Guangzhou [87], the south face was most popular in all conditions. However, in the RCP8.5 scenario, more cases would prefer the north orientation to avoid direct beam exposure. The geometric design parameters suggest a preference for deep and low-height spaces to reduce exposure to solar radiation. Barea et al. [128] discovered that rotating buildings (180 degrees) in Argentina would be most effective for the RCP8.5 in the 2099 future scenario, reducing direct solar gains by 73.1 %. Yan et al. [105] reported that an optimal south-easterly orientation would be preferable for future scenarios when compared to the south orientation of the base case. However, changing building orientation is typically only feasible for new constructions or in cases of complete rebuilding. For existing buildings, such changes are generally not possible due to site constraints, urban planning regulations, and prohibitive costs. This underscores the importance of considering climate change in the initial design phase of new buildings, as orientation decisions made at the outset will have long-lasting impacts on energy performance.

3.1.9. *Infiltration*

Infiltration rate refers to the ability of air to exchange between indoor and outdoor environments. Pérez-Andreu et al. [65] emphasized the necessity of solid construction to minimize infiltration, a critical requirement for achieving nearly-zero buildings in a changing climate, as it and enhanced insulation have significant energy-saving potential. Liu et al. [35] recommended improving the airtightness of buildings for future climate conditions. In regions like Hong Kong, where residential buildings often exhibit poor airtightness, enhancing infiltration levels emerges as a cost-effective strategy. Shen et al. [19] highlighted the significance of infiltration levels as the primary ECM affecting building energy use across various building types. However, it is essential to balance airtightness with cost considerations, as excessively tight construction may make retrofits less lucrative over the life cycle. Furthermore, the effectiveness of airtightness and insulation strategies may vary significantly depending on the building’s operation mode – fully air-conditioned, free-running, or mixed-mode. For fully air-conditioned buildings, increased airtightness can be beneficial in hot, dry areas where cooling demand is dominant and has surged under global warming. Conversely, free-running buildings in temperate climates may benefit from higher infiltration rates, utilizing natural ventilation and passive cooling to regulate indoor temperatures. Mixed-mode buildings require a balance between airtightness during air-conditioning operation and heat dissipation during natural ventilation periods. The complexity of this equilibrium is further exacerbated as climate change alters environmental parameters. Therefore, the optimal airtightness strategy should consider the local climate under climate change and the operational mode to balance energy efficiency, indoor air quality, and thermal comfort.

3.1.10. *Occupant behavior*

Occupant behavior significantly influences the indoor climate, which in turn affects the building energy demand. This behavior varies based on factors such as socio-economic status and the availability and affordability of cooling. According to Zhang et al. [155], energy savings potential through occupant behavior adjustments ranges from 10-25 % in residential buildings and 5–30 % in commercial buildings. These behaviors encompass a variety of actions and preferences, including thermostat settings, use of window blinds, and clothing choices.

The adjustment of heating and cooling setpoints has been extensively studied. Tsoka et al. [141] found that raising the cooling setpoint by 1.0 ℃ would reduce the future building energy demand by 6.0–7.5 %, whereas lowering the heating setpoint by 1.0 ℃ would result in an 8.5–14.1 % decrease in the future energy demand. Therefore, decreasing the heating setpoints would have a more significant impact on future energy reduction than increasing the cooling setpoints. This finding aligns with a study in Canada [34], which attributed this to the prolonged duration of heating periods and the heightened extreme cold climatic conditions in Canada. However, in future climate scenarios, elevating the cooling setpoints can lead to marginally more substantial energy savings, whereas global warming would diminish the effect of lowering the heating setpoints. Waddicor et al. [75] found that adjusting the cooling setpoint from 25℃ to 26℃ and 28℃ resulted in a significant reduction in cooling demand, decreasing from 33.1 to 21.1 and 15.3 (more than a half reduction) kWh/m^2. In future climate scenarios, climate change will magnify the importance of increasing the cooling setpoint and redue the significance of modifying the heating setpoint.

As evidenced by [34], adjusting setpoints would compromise the comfort level as measured by the hourly predicted mean votes. Specifically, decreasing the heating setpoint from 21℃ to 20℃ resulted in a 67 %, 39 % and 27 % greater proportion of uncomfortable zones in Quebec, Toronto and Vancouver, respectively. In comparison, the values are 24 %, 51 % and 25 % if increasing the cooling setpoint from 24℃ to 25℃. Therefore, investigations may need to encompass additional considerations such as thermal comfort and the socio-economic dimensions of occupants' behavior within buildings to assess modifying setpoints as an ECM [13]. However, since occupants may adapt to the local warming climate to some extent, cooling setpoints may be set higher when adaptive thermal comfort is considered [112]. As evidenced by [47], the upper limit of adaptive thermal comfort would increase by 0.6℃ in July from the 2000 s to the 2080 s. Occupants may also naturally adapt their clothing choices, allowing for higher cooling setpoints without discomfort. This adaptive behavior could potentially offset some of the increased cooling demand predicted due to climate change. Bienvenido-Huertas et al. [21] observed significant energy reductions by employing the adaptive thermal model for setpoints, with 26 % reductions for heating, 73 % for cooling, and 57 % for total energy consumption compared to a static model.

3.1.11. *Operational strategies*

Operational strategies refer to those related to occupancy, schedules of HVAC, appliances, lighting, blinds, ventilation, and fans. Dino and Meral Akgül [134] considered three scenarios with different cooling setpoints and activation of natural ventilation. Similarly, different working use schedules (heating, cooling, and natural ventilation), and changing setpoints were explored for heating and cooling energy under global warming [135], as well as related environmental impacts [136]. The impact of ideal and worst case-scenarios (different use of night ventilation, equipment, blinds, lights and A/C) on final energy consumption has been investigated in [123,124]. Interestingly, the studies revealed that occupant behavior had a greater influence on energy performance than the effects of building design [123] and climate change impact [124]. Notably, the worst-case occupant scenario yielded an average energy consumption 2.5–3 times higher than that of the ideal occupant scenario [123,124].

Picard et al. [142] examined three occupant behavior scenarios: baseline, energy austerity, and energy wasteful. The different behavior assumptions include setting of setpoints, schedules of HVAC, appliances, hot water use and ceiling fans. The energy wasteful scenario could cause energy consumption to double compared to the standard scenario. However, the most influential global warming case only increased standard energy consumption by 15 % over the period 2080–2099, supporting that poor occupant behavior poses a greater challenge than climate change. Zou et al. [143] discussed the uncertainty in usage patterns of four different family structures (not employed, working family, and two types of multi-generational families) under shared socioeconomic pathway (SSP) scenarios. Ren et al. [144] explored two operational schedules for a couple with two children (full day and evening only) under current and future climates.

3.1.12. *Summary for passive ECMs*

To summarize, passive ECMs aim to minimize heat gain during the summer and heat loss during the winter while moderating temperature fluctuations. The reviewed studies found that climate change has a dynamic impact on the effectiveness of passive ECMs. Consequently, strategies to address the implications of global warming through ECMs should be tailored on a case-by-case basis rather than adopting a "one-size-fits-all" approach. For instance, cool roofs may be more appropriate in those areas where cooling energy dominates, as they lead to heating penalties in the winter. Green envelopes may face challenges in extreme climates, as their effectiveness depends on vegetation health and survival.

In addition, ECMs considered unfavorable presently may evolve into energy-efficient solutions in the future, and vice versa. For instance, Pajek et al. [39] reported that improving SHGC to 0.20 led to an increase in total energy in the current climate due to the increased heating outweighing the cooling savings, but the intervention became energy-efficient after mid-century. The same penalty trend was observed for cool envelope strategies. These penalties might not persist if combined with other measures, such as night ventilation or improved insulation. This suggests that individual ECM should be evaluated in the context of complementary measures. The penalty experienced in the current situation may improve energy efficiency in future climates when cooling needs surge significantly. This underscores the significance of assessing the long-term effectiveness of ECMs, emphasizing the utilization of LCA methods to evaluate environmental impacts rather than solely relying on short-term outcomes.

In addition, these technologies need to be implemented at cross-country and cross-climate zone levels, considering their development without specific climate or building type considerations [25]. While technological advancements and building designs undoubtedly play pivotal roles, the efficacy of these measures can be significantly enhanced or hindered by occupant behavior. Educating and informing occupants and fostering awareness of energy efficiency are key steps in promoting sustainable behavior. For example, natural ventilation could have the potential to reduce cooling needs while also presenting adverse effects if outdoor temperatures surpass indoor ones. Furthermore, integrating smart and automation systems can further optimize energy consumption by adapting to occupants' preferences and environmental conditions.

3.2. *Active systems*

Active ECMs involve the implementation of mechanical systems to enhance building energy efficiency, with the installation or upgrade of HVAC systems being a prominent example.

3.2.1. *HVAC systems*

There are notable variations in energy sources, with some systems utilizing natural gas for heating while others opt for electrification in the heating process. Studies by [49,131,139,146,147,149] explored various HVAC system configurations as active ECMs, considering factors such as district heating, electrified heating, and heat pumps. Rahif et al. [139] showed that the electricity-based strategy reduced GHG emissions by 15–27 % and primary energy consumption by 6–13 % compared to the fossil fuel-based strategy. Similarly, Tarroja et al. [146] also indicated that electrified heating would reduce 30–40 % of GHG emissions. These studies highlighted the importance of decarbonizing the electricity sector and electrifying the building sector. With renewable sources dominating electricity generation, the increased future electricity demand would have minimal impacts on GHG emissions. However, challenges such as cost, rebound effect and increased grid resource capacity need to be addressed. Heating electrification loads occur when renewable photovoltaics (PV) generation is insufficient (winter) [146]. Berardi and Jafarpur [156] argued that the substantial cost differential between natural gas and electricity posed a challenge to the electrification of heating in Canada.

3.2.2. Efficient chiller

The efficiency of A/C systems has improved, with split-type air conditioners seeing an annual improvement of 3 % over the past 15 years in Asian, European, American, and Australian markets [157]. This tendency is expected to continue in A/C systems in the future. Consequently, the impact of efficient chillers on future thermal performance has been investigated as an active ECM. Improving the coefficient of performance of the chiller from 3.0 to 6.0 resulted in a significant energy saving of about 16 kWh/m^2 in total primary energy [75]. Barea et al. [128] investigated technological advancements in chiller coefficient of performance, projecting an increase from 2.3 in 2020 to 3.5 in 2075 and 4.4 in 2099. The study reported that cooling energy in Argentina would drop to even lower levels than today. However, it is essential to note that while improving A/C efficiency is important, the widespread uptake of cooling devices in regions previously without them could significantly increase overall energy demand. Studies such as [10] have shown that the proliferation of these devices in regions experiencing warming could lead to substantial increases in energy consumption, which is amplified by population growth.

3.2.3. Internal heat gain (IHG)

IHG is the heat source within a building that increases its thermal load. ECM for IHG includes investigating the energy efficiency level of electrical equipment and lighting, which generate heat during operation or illumination. Energy-efficient lighting and appliances are becoming more prominent in well-insulated buildings due to the significant effect of IHG on summer overheating.

Studies by [13,30,88,150] highlight the potential for reducing energy consumption by addressing internal heat loads. Li et al. [13] reported that reducing the lighting intensity in non-domestic buildings would have great potential to save energy (except for severe cold regions). Berger et al. [150] also supported that the impact of efficient lighting and equipment exceeded the implications of global warming on the net cooling demands of sample office buildings. Daly et al. [30] indicated that different equipment intensities could lead to substantial variations in energy use, with high equipment intensity resulting in a 36 % increase and low intensity leading to a 20 % decrease in energy use. Additionally, a lighting upgrade yielded significant energy savings of 20.1–25.4 % across all locations. This emphasizes reducing heat gain to curb energy consumption and associated GHG emissions from office buildings, as highlighted in [48,118,158]. Kolokotroni et al. [118] stated that reducing the IHG from a high to medium scenario would reduce carbon emissions from 480 % to 140 % in the city center location and 230 % to 87 % in the rural location in 2050.

Moreover, decreasing internal heat loads will influence heating and cooling demand by reducing heat emitted from lighting and equipment [31,32]. Jenkins et al. [151] showed that Scenario 2 (2005 + equipment interventions), compared to Scenario 1 (Baseline 2005 office), witnessed a great balance shift from using electricity for cooling to gas for heating. Heat gains from lighting and equipment might be more beneficial in colder climates than in warmer ones. Therefore, in areas where cooling needs are predominant (such as Hong Kong), reducing IHG is an effective strategy for office energy conservation. It not only decreases electricity consumption for lighting and equipment but also for cooling. However, the rebound effect often emerges simultaneously with improved energy efficiency, potentially partially or completely offsetting intended energy savings due to behavioral or operational changes. This underscores the need for a holistic approach that combines technological improvements with strategies to promote energy-conscious behavior and potentially limit rebound effects.

3.2.4. Heat recovery systems

Implementing a recovery system at 75 %, the residential building witnessed a 55 % reduction in energy demand [65]. However, this reduction was notably more dramatic in severe scenarios. In the study on a non-insulated reference building [90], heat recovery ventilation reduced total degree hours by 11 % in 2050 and by 12.1 % in the 2090 s.

3.2.5. Summary for active ECMs

Active ECMs primarily focus on enhancing system efficiency. The surge in cooling energy highlights the importance of improving the efficiency of HVAC systems and innovating alternative cooling technologies. Such initiatives not only reduce building energy consumption but also help alleviate the strain on the electricity grid, particularly considering the escalating frequency of extreme weather events. The phenomenon of IHG could exacerbate cooling demands, necessitating specific interventions, especially in urban offices in tropical climates. Addressing IHG not only decreases electricity consumption for lighting and equipment but also for cooling purposes. In addition, the efficiency of these systems is influenced by user behavior and rebound effects should be considered.

3.3. Renewable systems

The integration of renewable energy sources into buildings is gaining significance as a means to reduce reliance on conventional power sources. Although renewable integration does not inherently conserve energy such as electricity, it is essential to include renewables in the ECM discussion because using electricity from renewables results in lower primary energy consumption and associated carbon emissions compared to fossil fuels. Therefore, renewables should be considered as a broader ECM strategy. This encompasses technologies such as building-integrated PV systems, solar thermal systems, geothermal energy, and wind turbines.

Several studies have investigated the potential effects of climate change on building-integrated PV system performance in buildings. D'Agostino et al. [120] found building-integrated PV output increases of 3–20 % across European cities in 2060 climate scenarios. A similar trend is found in Australia [144] and the UK [50]. These increases are attributed to decreased cloud cover and rising solar radiation under global warming conditions [159]. However, the findings are not unanimous, with some studies reporting slight decreases in building-integrated PV energy output [160] or limited impact [161]. Furthermore, seasonal variability also plays a significant role, with substantial changes projected for summer months compared to winter [110].

The relationship between building-integrated PV output and building energy demand is complex and dynamic. According to a nearly zero energy building (nZEB) study [120], the excess energy production in future scenarios for 2060 would not be as high as before, as cooling needs increased due to global warming. Robert and Kummert [162] also stated that energy excess in summer decreased over time, and even energy shortages would occur in July 2050 as cooling increased. The low solar angles and reduced daylight hours during the winter do not generate sufficient heat. Both fall short for standard buildings and nZEB [120]. This highlights that reducing heating demand remains a crucial consideration in the design of nZEBs. It is worth noting that the heating loads in tropical areas may be less of a concern, as they may not require heating at all as average temperatures increase.

In addition to generating renewable electricity, incorporating renewable thermal energy sources is also imperative for building heating and cooling [25]. The use of heat pumps has gained prominence as an efficient alternative to traditional fossil fuel systems like boilers, as they can be three to four times more efficient [163]. Ground source heat pumps utilize the relatively constant temperature of shallow ground as a heat source in winter and a heat sink in summer. Martins and Bourne-Webb [131] considered eight scenarios involving air/ground source heat pump systems, personal comfort systems, and natural ventilation in the changing climate. Jylhä et al. [147] compared three system cases: 1) ground source heat pumps and borehole free cooling; 2) mechanical cooling with electrified heating; and 3) mechanical cooling with district heating. Luo and Oyedele [50] highlighted a growing trend in solar heater thermal power production, with an annual increase of around 30 kWh between 2021–2040 and 2061–2080, and 70 kWh from 1981 to 2000 to 2021–2040. For wind renewables, wind turbine energy production is intrinsically tied to wind speed trends. Results showed that the average wind power generation was 800 kWh during 1981–2000, which is higher than the average values of 650 kWh projected for the periods of 2021–2040 and 2061–2080 in Bristol [50].

These findings underscore the importance of considering the interaction between renewable energy systems and building energy demand when designing energy strategies for the future. Seasonal variations in building-integrated PV energy output and their alignment with heating and cooling demands are essential factors in optimizing year-round building energy performance. While renewable integration can significantly reduce reliance on fossil fuel-based energy sources, potential rebound effects and embodied emissions from system production should be considered in a comprehensive analysis of building energy performance.

4. Continuing challenges and emerging research frontiers

This section delves into challenges and emerging research frontiers that must be addressed to develop a more comprehensive and robust approach to climate change adaptation in the building sector. This part discusses issues related to economic analysis, resilient retrofitting, LCA, decision-making for climate-resilient buildings, and policy interventions.

4.1. Economic analysis of ECMs in climate adaptation

One of the main barriers to the widespread adoption of ECMs is the high upfront investment costs associated with many of these measures [39]. While there is a growing body of literature addressing the economic aspects of ECMs, there remains a need for more comprehensive and region-specific economic analyses, particularly in developing areas. For air-conditioned buildings in [114], there is a specific cost threshold for PCM implementation beyond which it ceases to be cost-effective. This economic aspect is particularly essential in developing regions like Africa, where many users may not be able to afford A/C, let alone the investment required for retrofits. Future research should prioritize cost-effective strategies suitable for these contexts.

The economic viability of ECMs can vary depending on the specific measure and the building type. For example, research indicates that roof insulation may be the most economically impactful ECM for residential buildings, whereas lighting efficiency could be the most significant for office buildings [19]. Similarly, the cost-effectiveness of different ECMs can vary depending on the specific technology and its implementation. Green roofs, for instance, have been shown to have relatively long payback periods, making cool roofs a more attractive alternative in many cases [43,137].

Occupant behavior is another essential factor that can significantly influence the economic performance of ECMs under global warming. Strategies such as modifying temperature setpoints have shown promise as cost-effective measures for reducing energy consumption and improving thermal comfort [31]. However, more research is needed to better understand the complex interactions between occupant behavior, building design, and ECM performance under climate change.

4.2. Climate resilient retrofitting

To achieve energy neutrality in the building stock by 2050, ambitious renovation measures need to be implemented. Research has suggested that the annual renovation rate of building envelopes should at least double to meet the 2030 target, regardless of the evolution of climate change and population growth [76]. This is also recognized in initiatives such as the European Union's "Renovation Wave" strategy [164]. However, the effectiveness of retrofitting measures in the face of climate change remains a challenge.

Retrofitted buildings usually combine multiple ECMs to form a retrofit scenario, as individual ECMs may not be able to prevent the need for cooling activation [90]. While certain combinations of ECMs, such as envelope insulation, cool roofs, selective window installation, and external shading, may be favorable for current climatic conditions [29], their impact on energy demand in future scenarios is less certain. Studies have observed that the cooling demand of retrofitted buildings often increases under future climate conditions, indicating a lack of resilience to the expected changes in average temperature and solar radiation [47,53,54,79,127].

This highlights a critical research gap in the development of robust and resilient retrofit solutions that can effectively manage energy consumption and reduce the risk of overheating in the face of future climate uncertainty. However, their implementation remains preferable to no action, given projections of even higher energy demand without retrofitting. Furthermore, while intervention is advisable, it's essential to recognize that future energy savings may be diminished compared to current conditions.

Rising average and peak temperatures highlight the importance of using innovative materials and technologies to curb the growth in cooling demand and electricity consumption. Moreover, considering the recent emergence of studies on the implications of climatic changes on building thermal performance, this review solely discusses ECM technologies that are examined within climate change studies. However, a broader array of emerging technologies, such as Trombe walls, movable blinds, and double skin façades, which have primarily been studied in past weather contexts, are not included in this list but warrant further discussion. In addition, the interaction of ECMs may also need further consideration. This needs investigation to determine whether the heating penalty in single ECMs like shading and SHGC indeed persists when combined with other ECMs like improved insulation and building control under climate change.

4.3. Integrating climate change into building LCA

Given that buildings often operate for more than 50 years and will inevitably face global warming, there is a call to promote LCA that considers global warming. The inclusion of climate change scenarios in LCA has been shown to result in significant differences in environmental impact indicators compared to benchmark scenarios [136,165].

The increasing focus on sustainability in construction has led to growing interest in the use of sustainable materials, particularly wood. The emergence of mass timber has made it a viable structural element for multi-storey buildings. However, the role of timber buildings in climate change mitigation is complex. Studies comparing the life cycle GHG emissions of concrete and timber buildings over their life cycle under climate change have yielded contradictory findings [113,166]. These contradictory findings can be mainly attributed to significant differences in GHG emissions throughout the embodied impacts (data source and quantity), the operational impacts (building thermal performance, lifespan, energy mix) and building system boundary. When considering time along with climate change, the biogenic carbon flow and the upstream aspects of forest management make the analysis extremely complex.

4.3.1. Dynamic energy mix

The dynamic transformation of the energy mix has the potential to greatly influence dynamic LCA. However, its exploration has been limited due to inherent uncertainties. Long-term scenarios involving diverse energy pathways can substantially alter the GHG coefficients of energy sources. To bridge this gap, researchers have implemented dynamic LCA to account for temporal variability [145]. The decarbonization of the electricity grid has been shown to have a much greater impact on LCA results compared to other factors such as higher cooling loads and climate scenarios [167,168].

Several studies have explored the impact of renewable energy scenarios on building LCA, demonstrating significant reductions in heating energy emissions and primary energy factors as the share of renewable energy increases [75,169]. However, predicting the development of green energy in the energy mix is challenging in the short term and highly complex in the long term. Factors such as the availability of local energy resources [71], socio-economic development, and international policymaking can all influence the uncertainty of energy mix scenarios [104]. The uncertainty will be less for countries where the energy is generated locally, as the energy emission factor is independent of any central electrical grid.

Although decreasing carbon intensity over time may lead to an overestimation of climate change impacts, placing reliance on technological progress remains precarious given its uncertain trajectory. Moreover, careful consideration is required when selecting energy mix scenarios, especially the 100 % renewable energy scenarios, which demand that the building sector align with their objectives [145]. Otherwise, the low electricity coefficient wouldn't effectively drive reduced building energy demand, leading to inconsistency with the scenario framework. As long as the electricity mix is not fossil-free, increasing electricity use will also increase fossil fuel use. Therefore, efforts to curb energy use should continue even with the electrification of end-users.

4.3.2. Dynamic energy demand

The dynamic nature of energy demand, varying across different time scales from seasonal to hourly, exerts a significant influence on a building's energy performance. Annual energy balance might not be a good enough indicator for accurately assessing building energy performance under global warming. While energy storage can effectively handle 24-hour fluctuations in loads, addressing longer periods exceeding three days becomes challenging [120]. This highlights the significance of considering the dynamic temporal relationship between building-integrated PV generation and building energy loads as influenced by climate change.

The dynamic nature of energy demand is further complicated by the aging and degradation of building envelope and HVAC systems throughout the building life cycle under climate change. The decreasing efficiency of a chiller due to aging had a more substantial effect on energy demand than climate change alone, with their combined impact increasing cooling demand by 100 % [75]. This dynamic effect is amplified by HVAC systems' decreasing efficiency under global warming, as studies [131,154,170] showed that the coefficient of performance decreased, further increasing cooling demand. Moreover, the growing frequency of extreme weather events risks overloading HVAC systems during peak conditions, potentially accelerating system degradation and further affecting energy demand patterns.

The implications of climatic changes on building energy are complex, extending beyond heating and cooling to include aspects such as domestic hot water demand and related solar heaters. About a 10 % decrease in water heating loads in buildings was reported [120] due to the increase in average shallow subsurface temperatures and water temperatures as a result of global warming and UHI [171].

Addressing the challenges posed by climate change involves ensuring that ECM is not only effective in the short-term for individual buildings but is also sustainable in the long-term trajectory of urban development. Population growth, technological advances, and lifestyle shifts need to be harmonized with the building energy demand, reflecting the multifaceted nature of the modern energy challenge. Specifically, population growth has led to increased housing and energy demand globally. Concurrently, the advent of big data and artificial intelligence has driven up power consumption by data centers and household appliances, exacerbating energy challenges. Moreover, the growing preference for electric vehicles, which can be charged using domestic plug-ins and powered by rooftop PV systems, may necessitate the introduction of a new module, B8, in building LCA [160,172]. This may necessitate introducing new ECM strategies, such as integrating energy storage systems into building energy management systems. Careful coordination and control strategies are necessary to optimize energy flows, particularly when coupled with electric vehicle charging and PV generation in buildings, to ensure efficient operation.

4.4. Trade-offs and decision-making for climate-resilient buildings

The utilization of computational power and advanced building simulation tools has significantly facilitated the optimization of building designs. However, climate change poses significant challenges for optimizing building energy performance and decision-making regarding ECMs due to the multifaceted nature of the criteria, trade-offs, and uncertainties involved.

As highlighted by several single-objective studies [88,127,133], optimized designs (ECMs) for present climates can exhibit considerable differences in energy performance when evaluated under projected future conditions, raising concerns about their long-term resilience and effectiveness. Apart from inherent future climatic uncertainties, factors such as occupant behaviors, HVAC system dynamics, and evolving energy mixes introduce additional layers of complexity and variability [83,173]. Consequently, evaluating the resilience and robustness of building designs to climate change becomes paramount.

Furthermore, multi-objective optimization approaches have revealed the instability and sensitivity of optimal solutions to climate change [46,49,54,55,62,87,105]. As evidenced in [54], a notable proportion of optimal models became suboptimal in future scenarios, with greater dispersion and instability observed under the more severe scenario. Decision-making is further complicated by the need to consider trade-offs between operational and embodied environmental impacts. Efforts to reduce operational impacts often adversely impact embodied impacts [174,175]. [Hence, the environmental implications of buildings in a future climate must not overlook embodied impacts, emphasizing the need for whole-life cycle building optimization, as emphasized by [35,50,52,104].

Moreover, real-world decision-making in building optimization must navigate the complexities beyond mere mathematical algorithms. Decision-making regarding ECMs under climate change necessitates a careful consideration of trade-offs between various objectives, such as environmental (e.g., energy, carbon, water), occupant health (e.g., thermal comfort, indoor air quality), productivity (e.g., lighting, acoustics), and economic factors. This may need to involve multi-criteria decision analysis. The selection and implementation of ECMs must account for broader social and equity considerations to ensure that the benefits are distributed equitably across various segments of society. The decision-making processes for ECM adoption for future climate-resilient buildings should be inclusive and participatory, actively engaging a diverse array of stakeholders, including building owners, occupants, community organizations, and marginalized groups. Top-down approaches that overlook the unique contexts, cultural values, and priorities of different communities risk prompting the adoption of ECMs that are ineffective, inappropriate, or create unintended burdens.

4.5. Tailoring ECMs to building types and scales

The review scope encompasses residential, office, and industrial buildings, with a primary focus on residential buildings. Different building types are typically investigated using representative models, such as those from ASHRAE Standard 90.1 [156,176,177]. The unique characteristics of each building type, such as energy sources, thermal performance, occupancy patterns, and internal loads, present distinct challenges and considerations for implementing ECMs. For instance, office buildings often have higher lighting and appliance loads compared to other building types [158,168], which can greatly influence their energy consumption and GHG emissions. A similar trend is observed in hospital building types [156]. Furthermore, the sensitivity of buildings to climate change can vary based on their size and internal load profiles, with smaller buildings often exhibiting greater sensitivity due to the higher proportion of energy consumption attributed to envelope heat loss/gain [156,176,178]. Fast food and sit-down restaurants, with higher ventilation rates and exposure of all zones to outdoor conditions, experience substantial cooling demand escalation [156].

However, it is important to recognize that mean and peak temperatures are not the only factors influencing building energy demand and thermal comfort. Humidity and solar radiation also play significant roles [179], and these variables are expected to change due to climate change. Cooling load is determined by both dry bulb temperature and humidity, which means that both sensible and latent heat need to be considered. This is particularly important in humid regions like Sydney and Brisbane [180], where the combination of high temperatures and humidity can significantly increase the demand for cooling. Moreover, the impact of humidity on thermal comfort and energy demand is not limited to residential and commercial buildings. In historic buildings, where the preservation of artworks is a primary concern, maintaining appropriate levels of relative humidity is essential. A study has shown that energy consumption in these buildings can rise by up to 15 % due to increases in relative humidity caused by global warming [181]. This highlights the importance of considering building-specific factors when designing and evaluating ECMs, rather than adopting a one-size-fits-all approach.

The review also emphasizes the need to assess the effectiveness of ECMs not only at the individual building level but also at the larger city and district scale. While certain measures, such as green roofs, may provide benefits for individual buildings, their impact on mitigating the UHI effect and reducing overall energy demand can only be fully realized when implemented collectively across a larger area [66]. However, this scale of implementation introduces additional complexities, such as accounting for population growth, the uptake of cooling devices, and dynamic building stock models, which require careful consideration and modelling [10,182]. City-level decarbonization efforts must consider microclimate and extreme weather conditions, as they can greatly strain peak energy demand and emissions. ECMs should effectively manage peak loads through strategies like advanced control systems and demand response programs such as pre-cooling. There is a need for more comparative cross-country studies that evaluate the performance of short-term and long-term effectiveness of ECMs across different building typologies, climates, and scales.

4.6. Policy interventions

The evolution of building codes and standards has resulted in a complex building stock with varying levels of thermal performance and resilience to climate change. Researchers globally have investigated how different building energy standards or construction codes respond to global warming [28,70,100,103,112,121]. These studies emphasize the significance of periodic updates of building codes to address the implications of climate change on buildings. Historical building codes traditionally prioritized winter heating energy over summer cooling, necessitating periodic updates and evaluations to remain relevant and effective in managing dynamic building energy demands driven by global warming.

To complement traditional building codes and mitigate the rebound effect, policymakers should undertake a range of interventions. These include mandating energy performance benchmarking and legislating improved communication of energy use. Financial policy measures could also be implemented, such as tiered pricing structures or penalties for excessive energy consumption. Moreover, demand-side management policies, including mandatory time-of-use pricing and requirements for smart grid integration, could shift consumption to off-peak hours under global warming. Such policies leverage social pressure and market forces to drive energy conservation. However, the interplay between different measures can have unintended consequences. Issues like energy poverty or affordable housing challenges can hinder building energy efficiency under global warming.

5. Conclusion and outlook

ECMs are frequently selected for their prompt benefits—alignment with existing climate conditions and swift economic gains. Yet, the durability of these measures is under scrutiny. As climate change progresses, it reshapes the climatic conditions that ECMs were tailored to, potentially rendering them obsolete or even detrimental. In addressing climate change adaptation for building energy systems, this review has provided a comprehensive overview of ECM strategies to mitigate building energy. This review primarily examined technical ECMs that have been incorporated in climate change studies within the existing literature.

ECMs encompass a diverse range of strategies, including passive, active, and renewable technologies. Among these, building envelope insulation and the thermal performance of windows are the most widely adopted ECMs in climate change studies. ECMs must be tailored to specific contexts, such as climate, building characteristics, and cost-effectiveness. The appropriate application of strategies, such as proper thermal transmittance and building airtightness, is significant for future building designs and depends on the local climate under global warming and operational modes of buildings. Furthermore, the surge in cooling demand in traditionally warm and cold climates has also emphasized the need for solar control strategies in the context of global warming.

HVAC systems play a crucial role as active ECMs, with studies investigating systems such as district heating, electrified heating, and heat pumps. Efficient chillers and strategies to mitigate IHG are needed to address rising cooling demands in warmer climates. For office buildings in these regions, the reduction of IHG may outweigh the implications of climate changes, as it not only reduces appliance and lighting electricity but also lowers cooling requirements. The integration of renewable energy sources (PV) into buildings emerges as a critical response to global warming. However, variations across seasons and regions underscore the need to address dynamic relationships between PV outputs and heating/cooling demands.

ECM selection and implementation must consider not only short-term factors but also long-term climate change projections. Low-cost interventions and empowering occupant behavior are critical to mitigating overheating and reducing energy consumption, particularly in low-income households. Meanwhile, the study also highlights several key challenges and barriers that hinder the widespread adoption of these measures under global warming:

1. **Resilience and robustness:** Various studies reveal a lack of resilience in retrofitted buildings to expected climate change impacts. Identifying the optimal solutions that will still be effective under future climate conditions highlights the need for robust and resilient building design under climate change uncertainty.
2. **Life cycle perspective**: ECMs beneficial in the present may become a disadvantage in the future, and vice versa. Therefore, indicators should not solely focus on single-year results, be it current or future, but instead employ a life cycle approach to quantify cumulative energy and GHG emissions. Additionally, there is a need to consider the embodied impacts of materials in building design, retrofit and optimization efforts.
3. **Localized ECM at multiple building scales:** ECM effectiveness should be assessed at both individual buildings and district scales. At individual levels, different building types present unique challenges due to varying characteristics, which are influenced by various climate parameters, such as humidity and solar radiation. The effectiveness of ECMs should also be assessed at district scales. This broader perspective introduces additional complexities, including

population growth, cooling device uptake, the rebound effect, and dynamic building stock.

4. **Potential energy shifts**: As the climate changes, the effectiveness of certain ECMs may diminish, necessitating strategic shifts. Passive cooling measures could become insufficient during more intense heat waves and significantly rising nighttime temperatures. This could prompt a transition to active cooling systems and a subsequent surge in electricity demand. In addition, solar control measures may become favorable as the average temperature increases in currently cold regions.

Shifting from one-size-fits-all to embracing a paradigm towards context-specific, whole lifecycle and flexible ECM is paramount to energy-efficient buildings at individual and district levels under climate change.

CRediT authorship contribution statement

Zhuocheng Duan: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Pieter de Wilde:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Shady Attia:** Writing – review & editing, Methodology. **Jian Zuo:** Writing – review & editing, Supervision.

Declaration of competing interest

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

Data availability

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

Appendix 1

Table A1

Existing literature reviews on the effect of climate change on building energy within the body of knowledge.

Reference	Year	Focus	Locations/Climates/ Buildings covered	Main findings
[12]	2012	Building adaptations to climate change Summary of A Special Issue	General	Existing regulations are based on past weather data Metrics should be handled carefully
[13]	2012	Building energy under global warming Mitigation and adaptation	General (Asia, Europe, U.S., Australia)	Hot summer and warm winter climate zone has the greatest adverse impacts Increasing summer setpoint temperatures and reducing lighting loads have mitigation potential
[14]	2013	Commercial buildings under the influence of climatic changes	Tropics and Commercial	Energy demand will increase in the tropics
[16]	2022	Meta-Analysis Overview of building typology, future scenarios, downscaling methods, and time period	General	Heating/cooling will decrease/increase
[15]	2023	Energy demand under climate change Future scenarios and downscaling methods	General (based on ANSI/ ASHRAE 169–2020)	Heating/cooling will decrease/increase Proposing a step-by-step process for future research.
[11]	2021	Passive and active technologies	Middle East	Energy and GHG emissions in warm-climate regions will increase Adoption of passive measures could reduce cooling demand in Middle East
[9]	2019	Renovation measures Implications of climatic changes for building energy and energy systems	General (developed and developing countries)	Up to 38 % energy reduction through passive and active refurbishment technologies
[183]	2019	Future weather generation methods Adaptation and mitigation factors	General	The gap between the impact of equipment modernization and design day considerations
[184]	2017	Future weather data	/	Present a seven points list of requirements for weather files Weather files for urban landscapes and assessments of severe events needing attention
[185]	2023	Energy consumption under climate change Adaptation Measures	Hot urban deserts	Insulation and efficient glazing are top strategies, with solar PV effective for primary energy demands.
[186]	2020	Different methods to assess the impact	/	Spatio-temporal changes need analyzed Create and share relevant datasets Subsequent effects should be considered
[187]	2021	Methods for creating future files Evolution of building energy demand Uncertainty quantification	General	Heating/cooling will decrease/increase Heating/cooling ratios need to be considered for adaptation measures
[188]	2020	Energy performance, comfort and heritage conservation	Historical building	Multi-criteria approach needed to select retrofit measures
[189]	2015	Indoor environmental quality and health under climate change	U.S. and Europe	Negative health impacts can be mitigated by changes to the building.

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