Environment, Development and Sustainability
https://doi.org/10.1007/s10668-024-04962-2

REVIEW

Climate change and the built environment - a systematic review

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Received: 16 May 2023 / Accepted: 21 April 2024

Abstract

Recent intergovernmental panel on climate change reports have once again emphasised the effective measures to reduce greenhouse gas emissions and the importance of the built environment. Historically, passive and active solutions are known for their potential to make the built environment more environmentally friendly. Recently, a significant number of studies covered the effectiveness of such solutions under distinct current and different future climate and emission predictions. Through the PRISMA framework, this paper presents a comprehensive state-of-the-art review of such studies within the last 10 years (2013–2023) to understand their impact, their tangible applications, and their empirical evidence. Local ecosystems, weather patterns, geographical and cultural challenges dictate the solutions for a warmer future. Among the solutions, as expected, passive solutions remain most effective even though a combination with active ones is necessary regardless of the context. The review in this paper is expandable beyond the effective reported solutions and it highlights the most effective solutions under different climate zones.

Keywords Climate change · Passive strategies · Active strategies · Built environment

1 Introduction

1.1 Review of intergovernmental panel on climate change (IPCC) reports

Once again, the significant impacts of anthropogenic activities in warming up the climate have been captured in the IPCC's Sixth Assessment Report (IPCC, 2021). CC is posing an increased frequency and intensity of heat waves, with irrevocable changes in dehydration, heat stroke and heat exhaustion, as well as mortality (IPCC, 2021; WMO & WHO, 2015). Inherently, humans will find all possible measures to mitigate these adverse effects, leading to an unprecedented increase in cooling demand

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Published online: 11 May 2024

and consequently greenhouse gas (GHG) emissions which further promote the CC (Mehmood et al., 2022). The increase of the GHG is responsible for an above-average surface temperature within the span of 1951–2010 (Climate Change, 2014: Synthesis, 2014). Thus, the IPCC has emphasised that more and more reduction in GHG is needed to avoid global temperature going beyond the 1.5 °C warming limit. In the Working Group III contribution to the Sixth Assessment Report, under the Summary for Policy Makers (SPM), section C.7.3, the IPCC asserts that bottom-up studies have shown that by 2050, up to 61% (8.2 Gt $C0_2$) of global building emissions can be alleviated (Shukla et al., 2022). Under the same section, the IPCC mentioned that sufficiency policies that avoid the demand for energy and materials contribute about 10% to this potential, while energy efficiency policies contribute about 42%, and renewable energy policies contribute about 9%. The report went on by saying that the largest portion of the mitigation potential of new buildings is available in developing countries while in developed countries the biggest mitigation potential lies within the retrofit of existing buildings. The 2020–2030 decade is critical for expediting the development of skills needed to fully capture the mitigation potential of buildings (IEA, 2018).

Even though peculiar mitigation potentials to the built environment are being developed, to stress the impact of CC, some scientific studies among numerous ones related to the science of the total environment in the literature have pointed out the solutions to mitigate the trend of environmental degradation arising from CC. For example, mitigations concerning the reduction in the loss of natural resources, like precipitation (Meshram et al., 2018) and reduction in the loss of potentials for sustainable rural and urban land usage, as well as wetland use (Aslam et al., 2023; Waqar et al., 2023, 2024a, 2024b; Zhao et al., 2023). Some studies also try to understand the effects of pollution on the environment arising from human behaviours affecting the climate, like black carbon aerosol contaminated air mass (Hussain et al., 2023); concentrations of polycyclic aromatic hydrocarbons (Ambade et al., 2021a, 2021b); concentrated particles matter (PM_{10} and $PM_{2.5}$) (Ambade, 2016; Ambade et al., 2022); and microbiological contamination (Naz et al., 2024). In all of these studies, the main objectives are to set aside measures in preparedness to combat CC in the near future.

Furthermore, in order to set a specific goal to widen the recognition of measures to combat CC, the IPCC in its Fifth Assessment Report (AR5) (Edenhofer et al., 2014), created Representative Concentration Pathways (RCP) scenarios to assess future possible risks and debate how decisions may influence the coming future. The RCP contain approximately thirty candidate scenarios, however, predominantly, four primary scenarios were reported by researchers (Bass & New, 2023; Vuuren et al., 2011). These four scenarios modelled by different climate groups across the globe are the RCP 8.5 RCP 6, RCP 4.5 and RCP 2.6 (Fig. 1). Each RCP defines a specific emissions pattern, the projected energy consumption and the subsequent radiative forcing (Moss et al., 2010). The radiative forcing in W/m^2 is the influence a factor has in tempering the balance of incoming and outgoing energy in the Earth-atmosphere system (Moss et al., 2010). The RCP 8.5 was developed in Austria, using the MESSAGE model and the Integrated Assessment Framework by the International Institute for Applied Systems Analysis (IIASA). It is characterised by increasing GHG over time and radiative forcing ($> 8.5\ W/m^2$), representative of scenarios in the literature that lead to high GHG concentration levels (Riahi et al., 2007). The RCP 6 was developed by the AIM modelling group at the National Institute for Environmental Studies (NIES) in Japan. It is known as a stabilisation scenario where total radiative forcing (W/m^2) is stabilised shortly after 2100, without further going beyond, through the

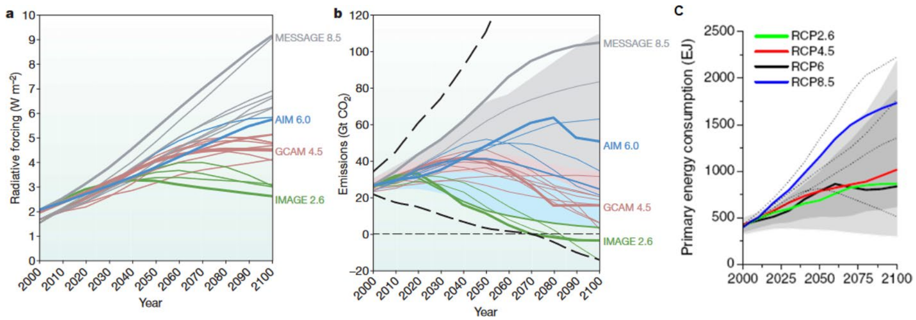

Fig. 1 Future emission, radiative forcing and primary energy consumption under different scenarios (Waqar et al., 2024b)

application of technologies and strategies for reducing GHG (Fujino et al., 2006; Hijioka et al., 2008).

The RCP 4.5 was developed by the GCM modelling group at the Pacific Northwest National Laboratory's Joint Global Change Research Institute (JGCRI) in the United States. It is also a stabilisation scenario, where the total radiative forcing (> 4.5 W/m^2) stabilises just after 2100, and also not going beyond the future radiative target level (Clarke et al., 2007; Smith & Wigley, 2006; Wise et al., 2009). The RCP 2.5 was developed by the IMAGE modelling group in the Netherlands. The emission pathway is representative of scenarios in the literature that lead to very low GHG concentration levels. It is a scenario which peaked and declined, having the highest radiative forcing level of (> 3.1 W/m^2) by 2050, and returns to 2.6 W/m^2 by 2100 (Vuuren et al., 2006, 2011).

The IPCC focus and evidences are essential to this paper to rigorously emphasize the potential of the foreseeable CC impacts to the built environment, and to understand the corresponding mitigation measures. Several studies have widely reported different passive, active and renewable measures used in the built environment (Cardinale et al., 2013; Herrera-Gomez & Quevedo-Nolasco, 2017; Pierangioli et al., 2017; Rañeses et al., 2021; Toe & Kubota, 2015). Only recently have some studies (due to the emerging global urge towards climate mitigations) focused on reviews of some past investigations which analyse the role of passive, active and renewable solutions in the built environment, and having practical applications in mitigating the effect of CC in the current and different future climate scenarios (Andric et al., 2019; Bass & New, 2023; Díaz-Lopez et al., 2022; Fereidani et al., 2021; Nair et al., 2022; Ozarisoy & Altan, 2021; Perez-Andreu et al., 2018; Soaresa et al., 2017; Zhou et al., 2020a, 2020b). This paper aims to provide a comprehensive evaluation of viable passive and active solutions that have demonstrated efficacy in CC mitigation and adaption.

1.2 Gap and contribution of this paper

Previous analyses on active and passive investigations to mitigating CC for either current or future scenarios, collated in past literature reviews have raised questions regarding the completeness of their analysis. For example, in a review paper by Andric et al., (2019), some investigations on passive and active strategies as well as their favourable impacts on renovation measures were reported under future climate scenarios. However, among the investigations on the strategies reviewed, the most recent was published in 2018 (Andric et al., 2018). Although, the review in Andric et al. (2019) summarily reported the impacts of some of the investigated passive strategies targeted toward future climate scenarios, the reported investigations were few (n = 13). Similarly, Fereidani et al., (2021) comprehensively reviewed a wide range of different passive and active strategies, but the review ended with a summary of a few reports (5 in number) where energy consumption on heating/cooling was included under future climate scenarios. In fact, among these reports, only one (Andric et al., 2020), published in 2020, explicitly discussed passive strategies (green roof, green wall, insulation and efficient window glazing) to address the impacts of future climate scenarios. Perez-Andreu et al., (2018) reported an in-exhaustive summary of CC's impact on heating and cooling demand, with some investigations amongst involved corresponding passive strategies to mitigate such impact. Comparable to the aforementioned reports in the reviews (Andric et al., 2019; Fereidani et al., 2021), the most recent of these investigations was published in 2017 (Pierangioli et al., 2017). Considering the period between 2017 and 2023, more investigations on passive and active strategies under future climate scenarios have been published and therefore a need for an update is necessary.

There are a limited number of studies that cover recent research on effective active and passive measures for CC mitigation. To the best of our knowledge, this is the first comprehensive update that includes the latest strategies specifically effective for warmer conditions. The specific contribution of this paper is an expandable, comprehensive and up-to-date review of CC mitigation measures.

2 Methodology

Initially, five combinations of keywords were used to retrieve records from the Scopus database the largest scientific database covering most of the peer-reviewed (Q1 and Q2) journals published by Elsevier, Springer, MDPI, SAGE, Wiley and Sons, Taylor & Francis. The searches were limited to a 10-year window period, covering all articles (journals and conference proceedings) published between 2013 and January 2023, in the English Language. The keyword combinations are climate change, built environment (2764 records); climate change, building operation, impact (395 records); climate change, building operation, built environment (83); climate change, buildings, passive solutions, active solutions (44); climate change, IPCC, built environment (17). These five keyword combinations were coined to reflect the specific goal and the filtering method proposed in this paper (Fig. 2).

A total of 3299 records were found and all records were exported to an Excel Package, where initial screening of duplicates and no Author(s) was conducted. All screenings were done using the method of the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) (Fig. 3). To justify the choice of PRISMA in this paper, a recent review study (Cui et al., 2022) on the effect of CC on critical infrastructure proved the PRISMA review system to be efficient in a systematic review where records of studies of interest are screened and deliberately categorised under different sections for in-depth analysis. Therefore, a total of 156 records were screened out for duplicates and no Author(s), and 3143 were the remainder. Studies which do not fall within the scope of the built environment (2700 records) were directly screened out right from the initial title screening stage, and a total number of 443 were remaining. These remainders were further meticulously and rigorously screened out in the abstract screening stage, with the target to extract the full-text studies which contain reports on

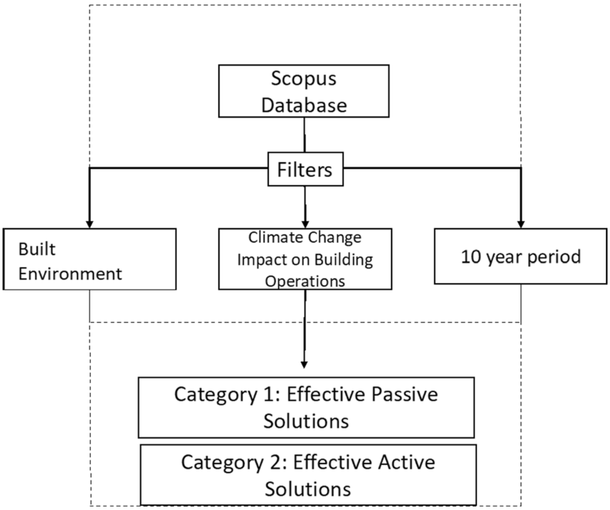

Fig. 2 Method for the filtering of studies included

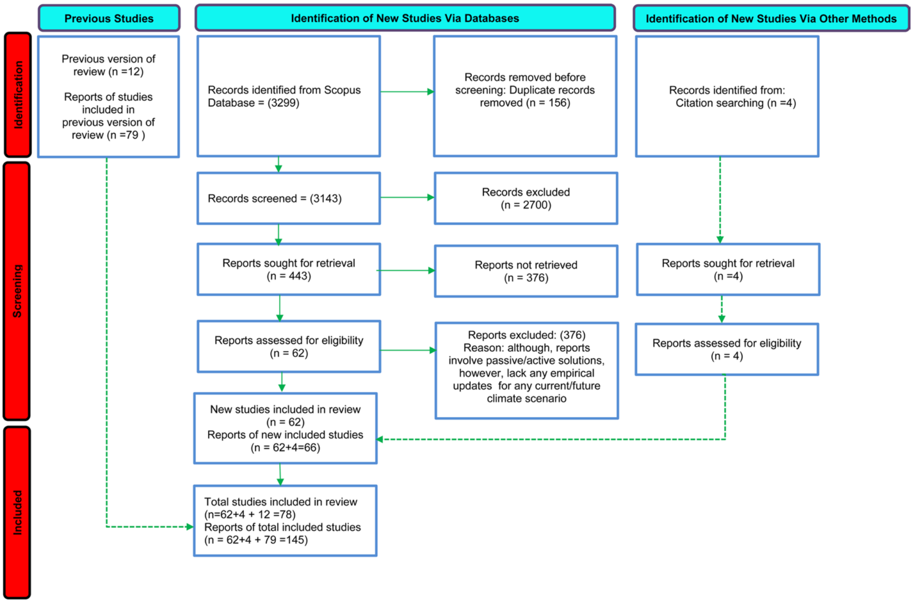

Fig. 3 PRISMA framework adopted in this study

passive, renewable active solutions, and 62 studies were recorded as new studies and reports. These new studies were considered for full eligibility as detailed in Fig. 3 by the PRISMA chart. This paper was only limited to passive and active solutions which reported only empirical investigations, and those without such were rather not retrieved. Because this paper is a systematic update, a further 12 reviews were separately screened and included as previous studies. These studies are termed as the previous version of the review (see Fig. 3). Some 79 reports from the previous version of the review were included as parts of the total reports of included studies. Other relevant 4 sources from citation searching were included. In all, a total number of 78 studies and 145 reports were recorded.

3 Results

This section encompasses the reports of the effective passive solutions and empirical findings cover the impacts of these effective solutions on both energy demand for cooling/heating and thermal comfort of occupants for current and future climate scenarios. A summary of key studies is provided in Table 1.

3.1 Category 1: effective passive solutions

3.1.1 Ventilation-related measures

Cui et al., (2022) used the Bayesian bootstrap as a promising technique to quantitatively evaluate the robustness of thermal comfort against uncertain future climate scenarios (the 2030s, 2050s and 2080s). However, the results concluded that adaptive night ventilation is potentially the key effective solution in all scenarios. Mehmood et al., (2022) conducted a study by using a two-story multi-family building as the baseline archetype in southern Asia, Pakistan. In order of importance, ventilative cooling, reflective and ventilated roofs, shading in windows, and roof insulation were the effective solutions for energy savings and reduction in discomfort hours, for 2020, 2050, and 2080 climate scenarios. The study reported that the passive solutions can improve energy demands from 13.1 to 7.1 kWh/m^2 and indoor discomfort from 320 to 131 h. In view of future higher temperatures (2050, 2080), Nunes and Giglio (2022) used Morris sensitivity analysis for a current and future climate and concluded that natural ventilation (Natural vent), solar absorptance of the envelope (Envelope$_{\text{Abs}}$) and thermal transmittance of the walls (Walls$_{\text{Trans}}$) respectively, are the most important parameters for the Degree Hour for Cooling (DHC); while Envelope$_{\text{Abs}}$ and Walls$_{\text{Trans}}$, in a respective order, are the most important parameters for energy savings with regards to cooling for all the climate scenarios. The Morris' elementary effect used by the author is summarised in the equations below to determine the indices $u, u^{*} and \sigma$:

$$u_i = \frac{1}{r}\sum_{j=1}^{r} d_i(x_j) \tag{1}$$

$$u_i^{*} = \frac{1}{r}\sum_{j=1}^{r} \left|d_i(x_j)\right| \tag{2}$$

$$\sigma_i = \sqrt{\frac{1}{r-1}\sum_{j=1}^{r} \left[d_i(x_j) - u_i\right]^2} \tag{3}$$

where i is variable; r is the number of samples path; j is each path in the sample space of each variable i; u_i is the mean of the elementary effects of the variable i; u^{*} is the mean, in

Table 1 Summary of reported studies

Full texts study	Location of study	Methodology	Effective solution	Empirical finding (energy demand/ energy savings/indoor comfort)	Climate periods/scenarios		Conversion model	Year
					Current	Future		
(Panel A)								
Cui et al., (2022)	UK, England	Bayesian Bootstrap	Passive	Overheating risk: Sensitivity analysis: $Natural_{vent}$	–	2030s, 2050s, 2080s	PROMETHEUS future design summer year (DSY)	2022
Mehmood et al., (2022)	Pakistan, Southern Asia	TRNSYS simulation ASHRAE	Passive	Energy demand: 36.9–78.1% by 2080; Energy savings: 13.1–7.1 kWh/m^2; Discomfort hours < 71.1%. (Ventilative cooling)	✓	2050, 2080	Morphing, CCWorld WeatherGen	2022
Nunes and Giglio (2022)	Brazil	EnergyPlus, Global Sensitivity Analysis	Passive	Sensitivity Analysis: Savings on Cooling: $Envelope_{Abs} > Walls_{Trans}$ DHC: Natural Vent > $Envelope_{Abs} > Walls_{Trans}$	✓	2020, 2050, 2080	Morphing, CCWorld WeatherGen	2022
Costanzoa et al., (2018)	Italy	EnergyPlus	Passive	Overheating reduced by 20% ($Hybrid_{vent}$, Insulation, double-glazed window)	✓	–	–	2018
Laouadi et al., (2020)	Canada	CIBSE, PHI	Passive	Overheating Risk: $Natural_{Vent}$ (26 °C) > Exterior Shade (above 28 °C) 26 °C: temperature for sleep Above 28 °C: Above temperature for sleep	✓	–	–	2020
Botti and Ramos (2017)	UK, York	IES-VE software CIBSE TM52	Passive	Overheating Risk: Sensitivity Analysis: Solar Shading > $Natural_{Vent}$ > Thermal Mass	✓	2030s,2050s, 2080s	PROMETHEUS future Design Summer Year (DSY)	2017
Heracleous et al., (2021)	Cyprus	IES-VE software	Passive/ Active	Reduction in DHC: 51% for current; 60% for 2050; 66.4% for 2090. ($Natural_{vent}$, HRV)	✓	2050,2090	Meteonorm	2021

Table 1 (continued)

Full texts study	Location of study	Methodology	Effective solution	Empirical finding (energy demand/ energy savings/indoor comfort)	Climate periods/scenarios		Conversion model	Year
					Current	Future		
Hamdy et al., (2017)	Netherlands	IDA-ICE version 4.6, MATLAB	Passive	Overheating Risk: Ventilative cooling rate (on Ave. 5 ACH): 90% reduction for current; 65% reduction for 2100	✓	2100	Royal Netherlands Meteorological Institute	2017
Roetzel et al., (2013)	Germany, Greece, Australia	EnergyPlus, ASHRAE Standard 55	Passive	Indoor comfort: WWR ≥ 70% above work plane; NNV ≥ 6 h; adaptive window operations by occupants	_	2030	Meteonorm	2014
Hooff et al., (2014)	Netherland	EnergyPlus	Passive	Overheating Risk: Exterior Solar shading > $Natural_{vent}$	✓	Representative (2006)	–	2014
Solgi et al., (2017)	Iran	EnergyPlus	Passive	Reduction of peak temperature by 6.5 °C and 4.38 °C (July and September) coupled with NNV	Generic	–	–	2017
Wang et al., (2017)	USA, DC	EnergyPlus	Passive/ Active	Energy savings: Mixed-mode Ventilation: reduction of 7.4% in 2080s; Combination of adaptive active: reduction of 2.5% in 2080s	✓	2020s,2050s, 2080s	Morphing, CCWorldWeatherGen	2017
Lapisa et al., (2018)	France (southern regions)	NSGA-II	Passive	Energy demand/discomfort (current and 2080): $Solar_{reflc.\ roof}$: albedo value (0.46–0.74 considering trade-off); Optimum NNV: set points of 18–26 °C; and Non-insulated ground slab	✓	2080	Morphing, CCWorldWeatherGen	2018
(Panel B)								
Yildiz (2015)	Turkey, Istanbul	Givoni's bioclimatic chart	Passive	Thermal comfort increase: TMY2 = 1.4%;2020s = 3.97%, 2050s = 4.75;,2080s = 5.95% ($Natural_{vent}$, Evaporative cooling, Thermal mass)	✓	2020s,2050s, 2080s	Morphing, CCWorldWeatherGen	2015

Table 1 (continued)

Full texts study	Location of study	Methodology	Effective solution	Empirical finding (energy demand/energy savings/indoor comfort)	Climate periods/scenarios		Conversion model	Year
					Current	Future		
Miri and Babakhani (2021)	Iran	OpenFOAM, SimScale, ASHRAE Standard-55 (2004)	Passive	Indoor comfort: Windcatcher: better than $Natural_{vent}$ and cooling systems with (window + door opening) by 101%	✓	–	–	2021
Pelletier and Calautit (2021)	Sydney, Australia	ANSYS Fluent 18.1	Passive	Indoor comfort: Windcatcher (HCHTD): airflow increase of 4% compared to ordinary windcatcher (HTD)	✓	–	–	2022
Ur Rehman et al., (2021)	Pakistan, Islamabad	TRNSYS simulation	Passive	Energy savings/Indoor comfort: PCM + corn husk wall: 27 °C $Temp_{indoor}$ compared to standard brick wall ($Temp_{indoor}$ 31 °C) 6% husk: 15.6% $Heating_{red}$:2.6% $Cooling_{red}$	Generic	–	–	2021
Meng et al., (2015)	Shanghai	Experiments, Thermocouple	Passive	Indoor comfort: PCM: Reduces $Temp_{indoor}$ fluctuation by 6.7 °C in summer and 12.7 °C in winter	Generic	–	–	2015
Wu et al., (2018)	Paris	Experiments, MATLAB-Simulink	Passive	Energy savings: PCHCM: 19.57% energy-saving potential rate	Generic	–	–	2018
Saffari et al., (2016)	Madrid	EnergyPlus, CondFD	Passive	Energy savings; 24 h HVAC operation + PCM melting point at 27 °C (10–15% annual savings)	Generic	–	–	2016
Chernousov and Chan (2016)	Hong Kong	EnergyPlus	Passive	Energy savings: Morning peak power: 5% reduction with PCM	Generic	–	–	2016

Table 1 (continued)

Full texts study	Location of study	Methodology	Effective solution	Empirical finding (energy demand/energy savings/indoor comfort)	Climate periods/scenarios		Conversion model	Year
					Current	Future		
Rahimpour et al., (2017)	Australia	EnergyPlus, CondFD	Passive	Energy savings: 24 h HVAC operation + 20 mm PCM thick in envelope: (21.8% annual savings in Hobart); (16.7% annual in Melbourne)	Generic	–	–	2017
Zeinelabdein et al., (2020)	Sudan, Khartoum	ANSYS Fluent simulation, EnergyPlus	Passive	Energy savings: Cooling load: PCM-FCS meets 42%; Energy: PCM-FCS leads to 67% savings	Generic	–	–	2020
Vega et al., (2022)	Chile	Experimental, EnergyPlus, CondFD	Passive	Energy savings: Electricity savings: PCM on walls and roofs (52.8% in Antofagasta and 36.3% in Calama)	Generic	_	–	2022
Zhao et al., (2019)	Tibet	Mathematical Model, MATLAB	Passive/Active	Energy savings: 24 h full heating + PCM + SHS (64% savings) Daytime heating + PCM + SHS (92% savings)	Generic	_	_	2019
Gallardo and Berardi (2022)	Canada, Toronto	Experiments, EnergyPlus	Passive/Active	Energy savings: RCP-PCM: passively absorbs 180-230wh/m^2 during the day; operates actively at nighttime	✓	–	–	2022
(Panel C)								
Zhou (2022)	Subtropical Hong Kong	TRNSYS simulation	Passive/Active	Energy saving: PCM on south façade: could reduce peak power by 2.4%; BIPVs: could reduce cooling load by 7.6% and peak power by 7.2%	✓	–	–	2022

Table 1 (continued)

Full texts study	Location of study	Methodology	Effective solution	Empirical finding (energy demand/energy savings/indoor comfort)	Climate periods/scenarios		Conversion model	Year
					Current	Future		
Al-Yasiri and Szabó (2022)	Iraq	Experiments, Thermocouple, Mathematical Model	Passive	Energy savings: Total heat gain: dropped by 56W with PCM $Temp_{indoor}$: enhanced by 2 °C during the day with PCM	✓	–	–	2022
Soudian and Berard (2019)	New York, Toronto	EnergyPlus	Passive	Energy savings: PCM + night ventilation(10 ACH): New York: EUI reduced by 7%Toronto: EUI reduced by 19.7%	✓	–	–	2019
Thantonga (2018)	Thailand, Bangkok	Experimental	Passive	Energy savings: Heat gain: reduced by 57.2% with SC-PCM compared to simple concrete wall	✓	–	–	2018
Sajjadian et al., (2015)	UK	EnergyPlus, DesignBuilder	Passive	Energy savings: Cooling savings: About 128.1kWh in August 2080 with PCM	✓	2020,2050, 2080	Morphing, CCWorldWeatherGen	2015
Calama-González Cet al., (2022)	Spain	Experimental MATLAB, Statistical Model	Passive	Comfort condition: ETICS = 36–39% comfort $DS_{façade}$ = 67–85% comfort	✓	–	–	2022
Guarda et al., (2019)	Brazil	ASHRAE Standard-55 (2013) Index	Passive	Comfort hours: Base-case typology: 17.9% by 2080 Typology with insulation: 27.2% by 2080	✓	2020, 2050, 2080	Morphing, CCWorldWeatherGen	2019
Lingard (2021)	UK	IES-VE software	Passive	Energy savings: Solid wall Insulation + Low U-value glazing: 65% savings on heating demand	Generic	–	–	2020
Cusenza et al., (2022)	Italy	TRNSYS	Passive/Active	Energy savings (GER): For CF + BIPVs (with battery storage) savings are 18% lower than XPS + BIPVs (no battery storage)	Generic	–	–	2022

Table 1 (continued)

Full texts study	Location of study	Methodology	Effective solution	Empirical finding (energy demand/ energy savings/indoor comfort)	Climate periods/scenarios		Conversion model	Year
					Current	Future		
Hugo et al., (2021)	South Africa	Experimental, ENVImet, IES-VE software	Passive	Energy savings/Comfort: Highly Insulated Model: ave. $Temp_{indoor}$ decreased by 0.7 °C; Highly Insulated Model + RTG: overall energy increased by 3.5% for current and 11% for 2100	✓	2100	Meteonorm	2021
Pierangioli et al., (2017)	Italy	EnergyPlus, DesignBuilder	Passive	Energy savings: ETICS + W_R = 70% savings compared with un-insulated base-case office building for the 2066–2095 climate scenario	✓	2036–2065,2066–2095	Morphing, COSMO-CLM Model	2017
(Panel D)								
Mahdy and Nikolopoulou, (2014)	Egypt	DesignBuilder	Passive	Energy savings/Comfort: Single reflective 6.4 mm glass(8% stainless steel cover) + < 10% WWR, for all climate scenarios	✓	2020,2050, 2080	Morphing, CCWorldWeatherGen	2014
Mahmoud et al., (2022)	Canada	DesignBuilder	Passive	Energy savings: Double glass low E 6/6 mm Air gap: 18.6% better than single clear reflective glass	Generic	–	–	2022
Pajek et al., (2022)	Athens, Porto, Moscow, Milan, Ljubljana	EnergyPlus, jEPlus Statistical Model	Passive	Energy Savings: Q_T and Q_{NH} = relevant parameter (U_0) Q_{NC} = relevant parameter (WFR), in all scenarios	✓	2020,2050, 2080	Morphing, CCWorldWeatherGen	2022

Table 1 (continued)

Full texts study	Location of study	Methodology	Effective solution	Empirical finding (energy demand/energy savings/indoor comfort)	Climate periods/scenarios		Conversion model	Year
					Current	Future		
Pajek and Košir (2021)	Slovenia Ljubljana	EnergyPlus, JEPlus	Passive	Energy savings (heating and cooling)/Overheating: $f_0 = 0.78$; DHC = 146 kJ/m^2/K; WFR = 15%, $U_w = 0.6 W/m^2K$; Natural $_{vent} = 8$ ACH; a $_{sol} = 0.4$, $U_0 = 0.1 W/m^2/K$; south-windows with shading, (for 2071–2100 period)	✓	2011–2040,2041–2070,2071–2100	Morphing, CCWorldWeath-erGen	2021
Cirrincion et al., (2021)	for Esch-sur-Alzette, Palermo	EnergyPlus	Passive	Energy savings/Indoor comfort Savings: with GRs, 20–50% for Esch-sur-Alzette, and 3–15% for Palermo; Comfort: reduction in PMVs and ceiling temperature (2–5 °C)	✓	2020,2050, 2080	Morphing, CCWorldWeath-erGen	2021
Cascone (2022)	Italy, Mediter-ranean	Experiments, Sensor	Passive	Indoor Comfort: Temp $_{indoor\ Surf.}$ = reduced by 2 °C with GRs compared with traditional roof	✓	–	–	2022
Sabati et al., (2020)	Australia	Experiment, DesignBuilder	Passive	Energy savings: Cooling savings: with GR, 13.5% savings compared with non-green roofs	✓	–	–	2020
Sartor and Calmon (2019)	Brazil	EnergyPlus	Passive	Energy savings: GR + Glass $_{reflc.}$ + Shading + Vent $_{facade}$ + Envelope$_{Abs}$ = 15% savings	Generic	–	–	2019
Andric et al., (2020)	Qatar	EnergyPlus, DesignBuilder	Passive	Energy savings: GRs + GWs = 3%XPS + Windows $_{en.eff.}$ = 30% cooling reduction	✓	2020, 2050, 2080	Morphing, CCWorldWeath-erGen	2020
Pokhrel et al., (2019)	Puerto Rico	WRF Model, EnergyPlus™	Passive/Active	Energy savings: Cool roof + modi-fying AC Temp $_{set\text{-}point}$ + efficient AC equipment = 40% savings	✓	–	–	2019

Table 1 (continued)

Full texts study	Location of study	Methodology	Effective solution	Empirical finding (energy demand/ energy savings/indoor comfort)	Climate periods/scenarios		Conversion model	Year
					Current	Future		
Kolokotroni et al., (2013)	UK, London	TRNSYS software	Passive	Energy savings: Cool roof optimum albedo = 0.6–0.7, air change rate = 2ACH: Heating/cooling saving of (3–6%)	✓	–	–	2013
(Panel E)								
Ortiz et al., (2022)	USA, New York	Building Energy Model, WRF	Passive	Energy savings: Reflective roof albedo (0.89) + Modifying AC $Temp_{set\text{-}point}$:20% savings	✓	2079	Central Park weather station	2022
Liu et al., (2021)	China	Field Measurement, Mathematical Model	Passive/ Active	Energy savings: Adjusting air tightness + Radiant floor heating: 84% savings on heating	✓	–	–	2020
Lucchino and Goia (2023)	Norway	Model-based Control, IDA ICE Model, Programming	Passive	Energy savings/comfort hours: 70% savings and > 80% comfort hours with MBC + DSF, compared to TBC + DSF	✓	–	–	2023
Ahmadian et al., (2022)	UK	CitySim Software	Passive	Energy Demand: Pavilion Built Form: demands 100kWh/m^2 by 2050; Tunnel-court Built Form: demands 45kWh/m^2 by 2050	✓	2050	Meteonorm	2022
Lei et al., (2022)	China	EnergyPlus	–	Overheating hours: 58–60% av. overheating hours by 2050 compared to 4–44% in current TMY	✓	2050	Morphing, CCWorldWeatherGen	2022
Hyung An et al., (2018)	Korea, Daegu	EnergyPlus	Active	Energy savings: Cooling/heating savings: with a-Si BIPVs based windows18.2% compared to clear glass double-layer glass window	✓	–	–	2018

Table 1 (continued)

Full texts study	Location of study	Methodology	Effective solution	Empirical finding (energy demand/ energy savings/indoor comfort)	Climate periods/scenarios		Conversion model	Year
					Current	Future		
Italos et al., (2022)	Cyprus	EnergyPlus, DesignBuilder	Active	Energy savings: With BIPVs, 63% of energy consumption is covered	Generic	–	–	2022
Kimiya Aram et al., (2022)	Iran	EnergyPlus Designuilder, NSGA-II	Active	Energy savings: with PV, 90% of energy demand be produced by 2080	✓	2080	Morphing, CCWorldWeatherGen	2022
Efthymiou et al., (2020)	Cyprus	EnergyPlus, Heat Transfer Equations	Active/Passive	Energy savings: With BIPV on DSF, a peak output of 80kKWp is produced to support all the 65KW cooling load	Generic	–	–	2020
Stockholm Chiu (2013)	Iran, Tehran	EnergyPlus, MATLAB	Active	Energy savings: Optimised RES with PV panels could decrease electricity demand in 2038 by 2.29% compared to RES design with present climate data	✓	2020, 2050	Morphing, CCWorldWeatherGen	2020
Perez-Andreu et al., (2018)	Valencia, Spain	TRNSYS software	Active/Passive	Energy savings: Passive model construction + HRS + Xtra $Mech_{vent}$: 80% savings in 2048–2052 period; 65% savings in 2096–2100 (regardless of the scenario in both cases)	✓	2048–2052, 2096–2100	Morphing	2018
(Panel F)								
Sobhani et al., (2020)	Stockholm, Sweden	TRNSYS software	Active	Energy savings: Active free cooling LHTES: meets 75% cooling requirement at half of electricity consumption	Generic	–	–	2013

Table 1 (continued)

Full texts study	Location of study	Methodology	Effective solution	Empirical finding (energy demand/ energy savings/indoor comfort)	Climate periods/scenarios		Conversion model	Year
					Current	Future		
Mostafazadeh et al., (2023)	Iran	EnergyPlus, MATLAB, prNSGA-III, Pareto optimisation	Active/Passive	Energy savings: Recommendations for all scenarios: 70-100 mm Thermal insulation thick (in floors and walls); triple glazed windows; GSHP and water-cooled chiller for AC, PS-20 PV panels, 20° and 27 °C heating and cooling set-points	✓	2050	Morphing, CCWorldWeatherGen	2023
Luo and Oyedele (2022)	Bristol, UK	GA-ANN	Active/Passive	Energy savings: Recommendations based on (2021–2040): Northavon House: 105 m^2 PV panel; 5 kW CHP system; 5.3 kW wind turbine; 38 kW biomass boiler, small thick insulation. Q Building: 81 m^2 PV panel, 10 kW CHP system, 19.2 kW wind turbine and 199 kW biomass boiler	✓	2021–2040, 2061–2080	Met office climate prediction model	2022
Rahif et al., (2022)	Brussels, Belgium	DesignBuilder, EnergyPlus JEPlus	Active	Energy saving: with reversible air-to-water heat pump (S02) 6–13% HVAC savings compared to gas-fired boiler + an air conditioner (S01)	✓	2050s,2090s	*Mod`ele Atmosph´erique R´egional* (MAR)	2022
Masi et al., (2021)	Italy	EnergyPlus	Active	Energy savings: PV panels: efficiency increases from 3.3KWp-6.9KWp under future scenarios		2041–2060	Morphing, Weathershift™	2021
Kharseh et al., (2015)	Stockholm, Doha, Istanbul	Earth Energy Designer, Hourly Analysis Program	Active	Energy savings: GSHP annual consumption: (-8.5% in the cold to 18% in the hot climate) from 2014–2050	✓	2050	Meteonorm	2015

Table 1 (continued)

Full texts study	Location of study	Methodology	Effective solution	Empirical finding (energy demand/energy savings/indoor comfort)	Climate periods/scenarios		Conversion model	Year
					Current	Future		
Shen and Lukes (2015)	USA	TRNSYS, eQuest software	Active	Energy savings: GW increase by 2–3 °C reduces the overall annual performance of GSHP in future warming scenarios in all cities	✓	2040–2069	Morphing	2015

Panel A: $Natural_{Vent}$ natural ventilation, $Hybrid_{vent}$ hybrid ventilation, *DHC* degree hour for cooling, *HRV* heat recovery ventilation, *AHC* air change rate, > descending order, $Envelope_{Abs}$ solar absorptance of the envelope, $Walls_{Trans}$ thermal transmittance of the walls, $Solar_{reflc.\ roof}$ solar reflectance of the roof, *NNV* naturalnight ventilation; Panel B: *TMY* typical meteorological year, *HCHTD* helical coil heat transfer device, *HTD* heat transfer device, *PCM* phase change material, $Temp_{indoor}$ indoor temperature, $Cooling_{red}$ cooling load reduction, $Heating_{red}$ heating load reduction, *BIPVs* building integrated photovoltaics, *HVAC* heating ventilation and air conditioning, *PCHCM* phase change humidity control material, *FCS* free cooling system, *SHS* solar heating system, *RPC* radiant panel ceiling; Panel C: *GER* global energy requirement, *EUI* energy use intensity, *SC* solar chimney, *CF* cellulose fiber, *BIPVs* building integrated photovoltaics, *XPS* extruded polystyrene, *RTG* roof top greenhouse, *ETICS* externally insulated systems, $DS_{façade}$ double skin façade, W_R high resistivity window; Panel D: *DHC* diurnal heat thermal storage capacity, U_w window thermal transmittance, $Natural_{vent}$ natural ventilation, *WWR* window-to-wall ratio, U_0 thermal transmittance of the opaque envelope, Q_{NC} cooling energy, Q_{NH} heating energy, Q_T total energy, *WFR* window-to-floor ratio, a_{sol} external surface solar absorptivity, f_0 building shape factor, *ACH* air change rate, $Temp_{indoor\ surf}$ indoor surface temperature, PMVs predicted mean vote, *GRs* green roofs, *GWs* green walls, $Windows_{en.eff}$ energy efficient windows, *WRF* weather research and forcast, *AC* $Temp_{set\text{-}point}$ air conditioning temperature set-point, $Vent_{facade}$ ventilated façade, $Glass_{reflc}$ reflective glass, $Envelope_{Abs}$ envelope absorptance; Panel E: *MBC* multi domain model-based control, *TBC* traditional-based controls, *DSF* double skin façade, *a-Si BIPVs* amorphous-Si building-integrated photovoltaic, *PV* photovoltaic, *TMY* typical meteorological year, *HRS* heat recovery system, *RES* renewable energy system, *Xtra* $Mech_{vent}$ extra mechanical ventilation; Panel F: *LHTES* latent heat thermal energy storage, *CHP* combined heat and power, *GSHP* ground source heat pump, *PV* photovoltaic, *GW* global warming absolute value, of the elementary effects of the variable i; σ_i is the standard deviation of the elementary effect of the variable i; $d_i(x_j)$ is the elementary effect of the *ith* variable in path j.

A comparison of u allows the identification of parameters which have more influence on the model response. The higher the u, the greater the influence, u^* being more comprehensive. Moreover, the σ_i allows the identification of parameters with nonlinear behaviour or those that interact with other parameters, and the higher σ_i the greater the interaction with other parameters, or more elaborate nonlinear behaviour.

For a current climate (2016), Costanzoa et al., (2018) compared the result of the overheating hour of an existing Passivhaus and found using a hybrid ventilation strategy instead of mechanical ventilation with heat recovery, lowering the insulating materials thickness (up to a third) applied to the roof and to the walls, as well as using double-glazed low-emissive windows in place of triple-glazed ones, is the best scenario analysis, and reduce the overheating hour to less than 20% compared to the existing building. In the study by Laouadi et al., (2020), indoor overheating guidelines of the Chartered Institute of Building Services Engineers (CIBSE) and the Passive House Institute (PHI) were used to compare the effect of natural ventilation (Natural vent) and exterior shade on overheating risk. With neutral nighttime temperature between 25 °C and 26 °C, according to CIBSE and PHI, the authors found that the natural ventilation significantly reduced the minimum nighttime temperature to 26 °C (close to neutral temperature for sleep) compared to exterior shade having nighttime temperature above 28 °C (This study only considers the current climate). Botti and Ramos (2017) used environmental solutions-virtual environment (IES-VE) simulation and sensitivity analysis to rank the effective measures of a care home. The findings show that solar shading, natural ventilation and thermal mass, respectively, are the most effective for current and future climate scenarios. Similar to Botti and Ramos (2017), Heracleous et al., (2021), also used IES-VE simulation to assess the potential of heat recovery ventilation and all other passive measures (e.g. cross ventilation; insulation on floor, wall, and roof; e-low glazing and shading devices), on the degree hour for cooling. The authors noted the combination of these measures could lead to a reduction in degree hour for cooling by 51% in the current climate, 60% in the 2050 period and 66.4% in the 2090 period. Hamdy et al., (2017) considered a current and future climate to test different ventilation rates in alleviating the risk of overheating in Dutch house stocks. A ventilative cooling rate of 5 Air change rate (ACH) on average, could reduce the overheating risk by 90% for the current climate, and 65% on average, for the future outdoor rising temperature (5.4 °C higher). For the climate scenario, A2 for 2030, Roetzel et al., (2013) identified typical patterns and key parameter optimisation for three climate zones across the world. Among the occupants' scenarios optimised, using an office cellular room, the result depicts that natural night ventilation of at least 6 h is optimum, and WWR above 70% could enhance the thermal comfort condition indoors for a future warmer climate. Although, Hooff et al., (2014), considered a future climate in a study which investigated a range of climate change adaption measures, but the future climate being considered was a representative one (2006 period). The authors claimed that the heat waves across this period could be similar to those of the possible future climate scenarios (e.g. IPCC A2 scenario). The results of the investigated adaption measures in the study showed that exterior solar shading followed by natural ventilation could significantly mitigate overheating. Solgi et al., (2017) conducted experiments on the benefits of night ventilation at 15 ACH with Phase Change Materials (PCM), and the peak temperature for two summer months, July and September, were reduced by 6.54 °C and 4.38 °C respectively. The study claimed that in the month of September, the peak temperature was reduced to 26.79 °C and also noted that this fell below the maximum threshold comfort temperature (28 °C). For a climate model CESM RCP 8.5, Wang et al., (2017) compared mixed-mode ventilation and adaptive active measures (the combination of adjustment of room temperature setpoint, HVAC operation hours and minimum airflow fractions of VAV boxes). The mixed-mode ventilation effective solution can reach a reduction of 7.4% (728.4 GJ) in whole building source energy use in 2080s in Washington DC, while the adaptive measures can reach a reduction of 2.5% (246.1 GJ) in whole building source energy use in 2080s in Washington DC.

Lapisa et al., (2020) identified parameter sensitivity for different passive cooling solutions using the Non-dominated Sorting Genetic Algorithm II (NDGA-II). The results emphasised that, for the southern regions of France, the optimum set point temperature considering natural night ventilation is 18–26 °C. Also, for a trade-off between energy demand and thermal discomfort for current and 2080, the authors suggested that the albedo value of the solar reflectance of the cool roof could be 0.46–0.74. For the minimised building primary energy consumption for heating and lighting (EP [kWh/m^2 /yr]) and degree-hours of summer thermal discomfort (DH [°Ch]) through the passive measures for the future climate scenario, the authors described the formulation of the objective function of the NDGA-II based on the number of objectives (*DH* and *EP*) in the following equations as:

$$f_{obj}(x) = \min\left(EP(x), DH(x)\right) \tag{4}$$

By the above objective function, the Pareto optimal solution was achieved through the trade-off of the objectives (*DH* and *EP*), normalized between the minimum and maximum values of the arbitrary coefficient ($R_{EP}, R_{DH},$) with respect to A,B with C as the possible optimal solution (Fig. 4).

$$\mathrm{A} = \left(R_{EP} = 0\right); \left(R_{DH} = 1\right) \tag{5}$$

$$\mathrm{B} = \left(R_{DH} = 0\right); \left(R_{EP} = 1\right) \tag{6}$$

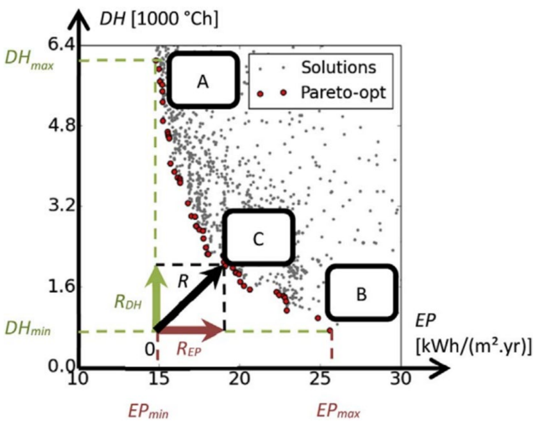

Fig. 4 Pareto optimal solutions and trade-off solution (A, B, C) (Andric et al., 2020)

$$C = \text{the trade - off between A and B} = \left\{ f(\vec{x})c = R_{EP}.EP\left(\vec{x}_{EP,R_{EP}}\right) + R_{DH}.DH(\vec{x}_{DH,R_{DH}}) \right\} \tag{7}$$

For R_{EP} and R_{DH} in A and B: $R_{EP} = 0$ (most energy efficient), $R_{DH} = 1$ (most summer discomfort hour), $R_{DH} = 0$ (least summer discomfort hour), $R_{EP} = 1$ (least energy efficient).

The trade-off solution C which is the Pareto optimal solution, C is represented in the study by a minimum value of $\overline{R}$ given as:

$$\overline{R} = \sqrt{R_{EP}^2 + R_{DH}^2} \tag{8}$$

where R_{EP} and R_{DH} are weighing factors which define the trade-off and were given in the study as:

$$R_{EP} = \frac{EP\left(\vec{x}_{EP,R_{EP}}\right)EP_{min}}{EP_{max\_}EP_{min}} \tag{9}$$

$$R_{DH} = \frac{DH\left(\vec{x}_{DH,R_{DH}}\right)\_DH_{min}}{DH_{max\_}DH_{min}} \tag{10}$$

Yildiz (2015) adopted Givoni's bioclimatic chart to assess the potential impacts of passive strategies on energy demand and thermal comfort level for different regions in Turkey. For the region of Istanbul, the potential use of evaporative cooling together with thermal mass and ventilation have been shown to have good promise to thermal comfort, with 1·4% for current typical meteorological year (TMY2), 3·97% for 2020s, 4·75% for 2050s and 5·95% for 2080.

Miri and Babakhani (2021) explored the potential of a vernacular windcatcher in a mountainous region, in the specific Mediterranean-to-cold climate in Western Iran to provide energy-efficient cooling and ventilation. By considering data from the current climate scenario, the authors explored the natural forces of wind and buoyancy using computational fluid dynamics (CFD), and the results of the investigation proved that in fact, the traditional windcatcher is more effective than the natural ventilation and cooling systems which are provided only through the openings of windows and doors by 101%, and its performance is comparable to modern wind catchers. Likewise, Pelletier and Calautit (2021) compared the performance of a windcatcher with a heat transfer device (HTD) to a windcatcher with a novel helical coil heat transfer device (HCHTD), however, under the current hot climate scenario in Sydney, Australia. After the analyses using a CFD simulation, the results showed that the windcatcher model with the HCHTD led to an increase of 4% airflow than the HTD model, which can achieve a comfortable level of cooling ranging from 14.25 K to 8.6 K for wind speeds of 1–4 m/s. It is also capable of meeting fresh air ventilation requirements in low wind speed scenarios. The authors further emphasised that, while the 4% increase in airflow might seem insignificant, it corresponds to a clear increase of 18 L/s of fresh air. This quantity of fresh air could double the required fresh air ventilation for a single occupant, the authors concluded.

3.1.2 Phase change materials (PCM) related measures

According to the summary of the overall passive measures in Table 1, from 1b to 1c, one can notice how PCM out-numbered the remaining passive measures. This stresses the importance that authors had given to the application of PCM on energy savings and thermal comfort. However, one limitation is that most investigations on PCM or PCM plus other measures are only based on the current or unspecified climate scenario (see Sect. 4 for more details). For example, without specifying any climate scenario (Chernousov & Chan, 2016; Meng et al., 2015; Rahimpoura, 2017; Saffari et al., 2016; Ur Rehman et al., 2021; Vega et al., 2022; Wu et al., 2018; Zeinelabdein et al., 2020; Zhao et al., 2019). Ur Rehman (Ur Rehman et al., 2021) compared corn husk composite material embedded with PCM, with standard brick construction, using a double-story school building located in Islamabad, Pakistan. The study found that 27 °C indoor comfort temperature was achieved without the need for mechanical cooling, and 31 °C was achieved for the standard brick construction. Meng et al., (2015) compared the fluctuation in indoor temperature for two identical hypothetical small rooms in China. One room without PCM and a new room with PCM (SP29 & RT18), and found that the new room with PCM can decrease the temperature fluctuation by 6.7 °C in summer and 12.7 °C in winter. Wu et al., (2018) used a couple of heat and moisture transfer (HAMT) models to test the energy-saving potentials of a phase change humidity control material (PCHCM) for different climate locations, but without specifying any climate period for the locations. After experimental validations of the base-case set-up, the study found that the maximal energy-saving potential rate of the PCHCM could be 19.57% for the Paris climate. Saffari et al., (2016) compared different PCM melting points (27 °C, 25 °C and 23 °C) against different HVAC operation schedules using a single zone base-case and also using the Madrid climate zone. For the 24 h HVAC operation schedule, the PCM with 27 °C melting point was found to achieve the highest annual energy savings of 10–15%, the 25 °C PCM melting point achieved 10–13% annual energy savings and the 23 °C PCM melting point achieved 8–10% annual energy savings. Considering the positioning of PCM in an office building in a generic climate of Hong Kong, Chernousov and Chan (Chernousov & Chan, 2016) considered its placement at the inner building envelope. This allows the PCM to reduce the morning peak power by up to about 5%. Rahimpour et al. (2017) devised the use of a 24 mm thick PCM in the roof, walls and floor as a demand response mechanism to reducing or shifting cooling and heating loads using three models; lightweight, brick-wall and PCM-enhanced lightweight buildings.. By using the CondFD algorithm, in the EnergyPlus platform, the results showed that the annual energy savings in Hobart and Melbourne (among the five cities analysed) are 21.8 and 16.7% respectively. Zeinelabdein (2020) investigates the potential of integrating PCM, as a Thermal Energy Storage (TES) with night cooling using computational fluid dynamics (CFD), and found the cooling system to meet 42% of the cooling load while also saving 67% of energy for the cooling requirement. By considering the parts of the works in the life cycle assessment of the integration of PCM in lightweight buildings conducted by Vega et al., (2022) in Chile, by also using the CondFD algorithm similar to (Rahimpoura, 2017), the findings showed that PCM integration in walls and roof decreases electric energy by 52.8% in Antofagasta and 36.3% in Calama. Zhao et al., (2019) investigated the integration of PCM with a solar heating system in a public building after studying the generic meteorological climate of Tibet. The study compared three schemes ('A', 'B' and 'C') of the solar heating system, and the results of the study concluded that the solar heating system, scheme 'A', integrated with the PCM led to 92% energy savings for a building requiring daytime (09.00 h-04.00 h) heating, and 64% energy savings for a building requiring 24 h full-time heating.

Contrary to the above studies, other studies only specified the current climate periods (Thantonga, 2018; Al-Yasiri & Szabó, 2022; Gallardo & Berardi, 2022; Soudian & Berard, 2019; Zhou, 2022), for example, in a study by Gallardo and Berardi (Gallardo & Berardi, 2022), using an experimental base-case set-up, an experimental procedure was used to test the energy savings of a Radiant Panel Ceiling PCM (RCP-PCM) in Toronto, Canada. The study concluded that the RCP-PCM can shift cooling load to off-peak hours, and can absorb heat gain between 180 and 230 wh/m^2. The study only compares the energy-saving potentials of the system for the current climate (September 2021). In the study by Zhou (2022), a dynamic transient dynamic platform was developed, integrating PCM walls with Building Integrated Photovoltaics (BIPVs). The results showed that due to solar shading, the vertical BIPVs may reduce building cooling load by 7.6% and peak power by 7.2%. The synergy of PCM walls and BIPVs could resist heat flux for a shorter period during summer time and provide heat for a longer period during winter time, with a higher magnitude in both cases when considering the current climate period. Al-Yasiri and Szabó (2022) investigated and compared the indoor temperature and heat gain reduction of two experimental setups (with and without PCM), in the current climate. The set-up with PCM proved to enhance the indoor temperature by 2 °C and reduce heat gain by 56W, compared to the set-up without PCM.

Similar to the night ventilation effect on PCM (Solgi et al., 2017; Zeinelabdein et al., 2020), and PCM integration with other measures (Rahimpoura, 2017; Gallardo & Berardi, 2022; Zhao et al., 2019; Zhou, 2022); Soudian and Berard (2019), compared different ventilation flow rates (0, 2, 5 and 10 ACH) for night ventilation to test the effect of PCM integrated in walls and ceiling for the current climates of Toronto and New York in the summer. For the ventilation flow rate of 10 ACH, the cooling energy use intensity (EUI) was reduced by 19.7% and 7% in both Toronto and New York respectively, compared to the baseline without PCM. The results also claimed that the 10 AHC ventilation flow rate performed better. Thantong (2018) also compared the energy-saving potentials of two house models. One with a solar chimney PCM (SC-PCM), and the other with a simple concrete wall. The result showed that ventilation reduced the heat gain by 57.2% through the south wall with SC-PCM compared to the simple concrete wall.

Again, contrary to all the studies above on PCM which only considered current or generic climates, Sajjadian et al., (2015) assessed the potential of PCM on energy savings and thermal comfort of a near Passivhaus standard building in the UK, for current and future climate scenarios (2020, 2050, 2080). The results indicated that in the summer month of August 2080, cooling load savings of up to 128.1 kWh could be attained.

3.1.3 Insulation-related measures

Although, while investigations of some studies showed how insulations performed better as a passive solution than other passive strategies, others showed a contrast. For example, considering the current climate scenario, Calama-González et al., (2022) compared the performance of an externally insulated façade with a double skin façade (DSF) on the south and north façades of a building. The authors found that the double skin façade provides 67–85% comfort condition compared to the externally insulated façade with a comfort condition of 36–39%. However, since this study only considered the current climate, other different possibilities may arise for other future climate scenarios. Conversely, by considering the current and future climate scenarios, Guarda et al., (2019) compared the performances of typologies with rock wool, glass wool and Expanded Polystyrene (EPS) insulations against a base typology without any insulation. For the 2080 scenario, the authors confirmed that the base case typology can only achieve 17.9% comfort hours, while the rock wool, glass wool, and EPS typologies achieved 27.2%, 27.2% and 24.9%, respectively. The authors also noted that in all the climate scenarios, the glass wool and rock wool present the same performances. Again, without specifically relating to any climate scenario, Lingard (2021) confirmed the performance of solid wall insulation with low U-value glazing as a retrofitting option for the UK housing stock. The study found that retrofitting could reduce heat pump heating demand by 65%.

In a study on the impact of environment and energy of a net zero energy residential building, Cusenza et al., (2022) compared the performances of four design scenarios. The main outcome of the study showed that cellulose fibre insulation with BIPVs (with battery storage) has the lowest global energy requirement (GER), which is 18% lower than the expanded polystyrene (XPS) insulation with BIPVs (without battery storage). Contrary to the above study where integration of well insulation-based model designs gave rise to better energy savings, remarkable unprecedented results documented by Hugo et al., (2021) on the performance of a highly insulated model shows that, while there was about 0.73 °C decrease in average indoor temperature in the highly insulated model, the energy consumption increases by 3.5% when retrofitted with a roof top greenhouse (RTG) in the current climate scenario. In fact, the study further documented that by 2100, the energy consumption in the highly insulated model with the retrofit measure will rise up by 11% for the climate scenario of 2100. For a more continuous favourable performance of highly insulated buildings, the authors finally recommended an appropriate choice of RTG for any retrofit measure for the peculiar climate scenarios of Southern African cities. On further arguments on the performance of insulation-based measures against other passive measure, i.e., double-skin facade, contrary to the study in Sajjadian et al. (2015), Pierangioli et al., (2017) argued that an externally insulated system plus a high resistance window performed better in terms of energy savings than other passive measures in all cases including office buildings and two residential buildings. The results of the study showed a reduction of 64%, 67% and 70% energy savings for the two residential buildings and the office buildings respectively, for the future climate scenario of 2066–2095. In each case, the results demonstrated the comparison of the externally-insulated systems integrated in the buildings with the un-insulated base cases. Although this study considered the current and future climate contrary to Calama-González et al., 2022, the reference climate is Central Italian and also does not consider a double skin façade as part of the compared passive measures.

3.1.4 Fenestration, roof and other related measures

Mahdy and Nikolopoulou (2014) compared the performances of combining different window to wall ratios (WWR) and glass types of window openings, in different climate zones in Egypt, under current and three future climate scenarios (2020, 2050, 2080). According to the findings of the investigation, by considering all the climate scenarios, $<10\%$ WWR with a 6.4 mm glass reflective glass (having 8% stainless steel glass) could provide the best energy consumption (minimum) while maintaining better thermal comfort condition for all the climate scenarios. Similarly, Mahmoud et al., (2022) also investigated the performances of different glass types on energy consumption, although, in the cold climate of Canada and future climate scenarios were not considered. The results of the investigation showed that Double glass low E 6/6 mm Air gap is 18.63% better than the single clear reflective glass of the base-case yearly, in terms of energy consumption. Using a statistical Multiple Linear Regression model and a least-square estimate, Pajek et al., (2022), conducted a test of several passive design parameters to assess their relevance on energy consumption on heating, cooling and total energy consumption, across five countries in Europe (Ljubljana, Athens, Porto, Milan, Moscow) and under three future climate scenarios (2020, 2050, 2080). The assessments concluded that the U-value of the opaque envelope (thermal transmittance) was the most relevant parameter influencing the total energy consumption and the energy demand on heating, while the window-to-floor area (WFR) was the most relevant parameter for the cooling load. More so, in an earlier study, Pajek and Košir (2021) compared the performances of three building models with the same usable floor areas on energy savings and overheating for current and future climate scenarios, according to the Slovenian Energy Performance Certificate classification. According to the results of the study, the model with the best overall performance especially in view of the future climate scenario, meets the recommendation of the passive design parameters (Table 1), with the WFR at 15%.

Cirrincion et al., (2021) compared the effect of green roofs (GRs) installed on buildings and standard buildings without GRs, with respect to climate change and demographic growth, in the cities of Italy and Luxembourg. The effects of the GRs showed a 20–50% and 3–15% reduction in energy savings in Esch-sur-Alzette and Palermo respectively. For indoor comfort, the results of the study further showed that, with the presence of the GRs, there was a shift in the thermal sensation of PMV from an acceptable-moderate level (PMV $\geq$ 0.5) to a moderate-normal level (PMV $\leq$ 0.5). In contrast, Cascone (2022) only consider the current climate by comparing the performance of a bio-based GR (recycled polyethene granules) with a commercially traditional one in the Mediterranean climate in Italy. By using experimental set-up and measurements with sensors, the author detailed that the bio-based GR led to a reduction of 2 °C in the indoor surface temperature as compared to the traditional roof, as well as a corresponding reduction in energy consumption. Similarly, Sabati et al., (2020) also considered the current climate scenario and used an experimental set-up involving heat flux sensors and thermocouples, to compare the performance of rooftop greenery systems (RTGS) with non-green rooftops in a sub-tropical climate in Australia. Based on the comparison, the cooling load result using the DesignBuilder simulation showed that a reduction of 13.5% in energy could be saved with RTGS. By considering the integration of GR with other passive measures as retrofitting intervention, Sartor and Calmon (2019), in a generic climate in Brazil, have shown that the overall performance of all the measures on a neighbourhood building achieved a 15% reduction in energy consumption. However, in this case, the impact of the GR is very minute, contributing to only a 0.2% reduction, while the ventilated façade had the highest significance, contributing to about 10%. Andric et al., (2020) were the first and only authors to study the energy performance of green systems (on roofs and walls) for the current and future climate in Qatar. The authors modelled a two-story residential building to serve as a representative building stock of Qatar (2020, 2050, 2080). After documenting the projected energy consumption of the building without mitigation measures (increase by up to 9%, 17%, and 30% in 2020, 2050, and 2080, respectively), the study concluded that integrating a 50 mm XPS and the installation of energy-efficient windows (30% energy savings) proved more energy efficient than the addition of green systems on walls and roofs (3% energy savings) under the climate condition. Although, this study contradicts others on the performance of green systems.

Away from green roof systems, cool roofs, based on their albedo parameter, have also shown promise in reducing energy consumption and enhancing comfort. For example, Pokhrel et al., (2019) explored the combination of active and passive building energy sustainability and mitigating options, using the weather research and forecast (WRF) model, with the building effect parameterization and building energy model (BEP-BEM) schemes, under the current climate. Based on the mitigating options explored, the findings showed that the cool roof, control of indoor temperature set-point and the use of efficient air-conditioning (AC) equipment reduced the total energy demand by 6.9%, 9.9% and 16.15%, respectively. When simultaneously considering all options, the result also showed that the total energy could be reduced by 40%. Again, in the study conducted by Kolokotroni et al., (2013), on the impacts of different albedo values for the cool roof, and under the current climate scenario, the simulation results showed that the realistic optimum albedo value to achieve about 3–6% overall heating and cooling reduction is 0.6–0.7. Together with this value, the authors also recommended an air change rate of 2ACH. On the contrary, Ortiz et al., (2022), instead suggested that a reflective roof with an albedo of 0.89 combined with AC set-point adjustment could lead to a 20% reduction in cooling energy demand in the highest-burden neighbourhoods in New York, under a warming climate. The results of this study were based on the current and future climate scenarios, using the Weather Research and Forcast (WRF) model.

In a study on the impact of air infiltration rate on heating demand, Liu et al., (2021) first conducted a comprehensive field investigation into the space heating performance of airport terminals across various cities in China. Through the potential of the adaptive passive strategy of adjusting air tightness, the study concluded that adjusting the air tightness at the top and bottom openings against severe infiltration rate, as well as using radiant floor heating could jointly lead to 84% energy savings on heating. Because the investigation in this study was conducted between 2012 and 2019, it is important to note that this study only focused on the current situation of the higher energy consumption for space heating in airport terminals.

Among some studies which used emerging control systems, Lucchino and Goia (2023) most recently used a multi-domain model-based control (MBC) algorithm for an adaptive façade based on a flexible double skin façade (DSF). Although, the study only considered the current climate for three seasonal periods (winter, summer and mid-summer). By using a Building energy simulation tool (BES) to co-simulate with the MBC to select the best DSF, the findings showed that the MBC could save 70% of energy while simultaneously maintaining occupied comfort hours > 80% (falling within the selected comfort criteria for all the domains). The authors claimed that these results are when comparing the MBC with other traditional control systems, i.e., schedule and rule-based controls. One can say the outcome of this study could not have been better emphasized if any future climate scenario had been adopted to test the performance of the MBC on the DFS. In the study, the authors considered four domain priorities (illuminance on the working plane, $\overline{E}_{plane}$; CO2 concentration in the room, Δ CO2; operative temperature in the room,T_{op}; as well as the heating and cooling demand,$|Q_{heat}| + |Q_{cool}|$) to check the performance of the adaptive DSF. Based on the domains, the controlled MBC optimisation problem on the performance of the DSF coupled with the HVAC system was formulated by the authors in Eqs. (11) and (12) thus:

$$\min\left(|Q_{\text{heat}}| + |Q_{\text{cool}}|\right)[OCC, AFP, OP, F, SH, \varphi] \tag{11}$$

where: $|Q_{heat}| + |Q_{cool}|$ is the sum of heating and cooling demand; *OCC* is the presence of the occupants; *AFP* is the possible airflow paths; *OP* is the position of the openings; *F*: is the fan settings (operation and flow); *SH* is the shading position; φ is the angle of the slats of the DSF.

Table 2 Threshold values for the MBC scheme: table adapted from (Hugo et al., 2021)

$\overline{E}_{plane}(Lux)$		$\Delta CO_2[PPM]$		$T_{OP}[°C]$	
$1^{st}LEVEL$	$2^{nd}LEVEL$	$1^{st}LEVEL$	$2^{nd}LEVEL$	$1^{st}LEVEL$	$2^{nd}LEVEL$
Office space	Circulation	II Class	III Class	II Class	III Class
500	300	800	1350	20–24	19–25
				23–26	22–27
				20–26	19–27

The threshold value of the T_{OP} vary based on the seasons (winter, summer and mid-summer)

Additionally, the four domains were subject to the following constraints:

$$\begin{cases} \overline{E}_{plane} > 1^{st}LEVEL_{limit} else \overline{E}_{plane} > 2^{nd}LEVEL_{limit}; \\ \Delta CO_2 \langle 1^{st}LEVEL_{limit} else \Delta CO_2 \rangle 2^{nd}LEVEL_{limit}; \\ 1^{st}LEVEL_{low-limit} < T_{OP} < 1^{st}LEVEL_{high-limit} \\ else \\ 2^{nd}LEVEL_{\text{low - limit}} < T_{OP} < 2^{nd}LEVEL_{\text{high - limit}} \end{cases} \tag{12}$$

Threshold values of 1st and 2nd LEVEL in Eq. (12) are presented in Table 2 based on the authors' assumptions:

For studies on building layout and form as effective passive measures, Ahmadian et al., (2022) developed an optimisation framework to identify the most energy-efficient built form and urban geometry for the future built environment which can adapt to the changing climate scenarios. Among the four built forms optimised, compared to the pavilion built form (least efficient), the tunnel-court form (most efficient) could lead to an energy demand of 45KWh/m^2 by 2050, and the pavilion could lead to an energy demand of 100WKh/m^2 by 2050.

Although the authors did not recommend any effective passive or active solution, Lei et al., (2022) projected the effect of climate change on thermal comfort in heritage apartments in both hot summer and cold climate zones in China, under the current (TMY) and future (2050) climate scenario. The authors found that an increase of 58–60% in the predicted average overheating hours is likely by 2050, compared to 4–44% overheating hours under the current climate scenario. They concluded that some climate change adaptation measures like solar shading, passive cooling and insulation, are currently studied in an ongoing study to mitigate the impact of overeating in view of any future climate scenario.

3.2 Category 2: effective active solutions

For PV-related active measures, Hyung An et al., (2018) compared the performances of heating and cooling loads of amorphous-Si (a-Si) building-integrated photovoltaic (BIPV) window (a-Si BIPV) and clear glass double-layer used in an office building in Korea for the current climate and concluded that the a-Si BIPV windows could reduce 18.2% energy demand on both cooling and heating compared to the double-layer windows. Italos et al., (2022) similarly conducted an energy performance analysis of an existing residential apartment by comparing two models. One with the integration of a double skin façade containing an effective active solar energy system (BIPVs), glazing system as well as rambling planting, and another model without. While this study focused on an unspecified climate scenario in Cyprus, parts of the results proved that the active solar energy system could cover the proposed energy consumption of the building by up to 63%. For the current and future climate, Kimiya Aram et al., (2022) also proved that the use of active PV solar systems in combination with other effective passive and active (efficient ACs) solutions, 65.14% and 86.18% energy consumption could be reduced in the current climate and future climate scenario of Iran. Also, the PV solar system could produce 90% of the building's energy demand by 2080. Furthermore, for an existing mixed-mode building in Cyprus, and also without a specified climate scenario, Efthymiou et al., (2020), saw the possibility of using active solar BIPVs (along with their effective operation) as passive shading devices, as part of a double shell. While the other passive measures (80 mm polystyrene insulation, PVC double glazing) account for 85% and 50% reduction in heating and cooling load, the energy output from the BIPVs could cover the remaining 50% of the cooling load. Stockholm Chiu et al., (2013) investigated whether the design of a renewable energy system (RES) based on present-day data could lead to efficient energy performance in a future climate scenario, using a passive representative building in Tehran, Iran. Firstly, part of the study showed that the design of a RES with present energy data is vulnerable to the impact of CC. Secondly, using an optimisation technique concerning the influence of future CC scenario (2038), the summarily of the authors' findings showed that the optimal RES (fit for the future climate scenario), decreased the annual electricity demand of the building by 2.29% between 2019 and 2038. The optimised RES share was also shown to cover the annual electricity demand shifts from 95.4% in 2019 to 102% in 2038, due to the growth of about 4.5% power generated by the PV systems, showing the reliability of the PV system over the long-term.

Perez-Andreu et al., (2018) conducted a comprehensive study for the current climate scenario (TMY2) and four temperature projections of two periods (2048–2052 and 2096–2100) under the following four climate-change scenarios: CNRM-CM5 RCP4.5, CNRM-CM5 RCP8.5, MPI-ESM-LR RCP4.5, and MPI-ESM-LR RCP8.5, in Valencia, Spain. The authors developed eight models based on a typical Mediterranean residential building to reflect a combination of different passive and active measures. Among all the models (including the base model), 'model 8', where all combinations of passive measures plus heat recovery system, as well as extra mechanical ventilation, were implemented, irrespective of climate scenario, the energy savings of at least 80% could be achieved in 2048–2052. Again, the authors' results showed that, in model 8, at least 65% energy savings could be achieved in the 2096–2100 period. The study also separately mentioned the contribution of adding the heat recovery system and the mechanical ventilation in model 8 to have 19% energy savings in the (MPI-ESM-LR RCP 8.5 scenario) in the 2096–2100 period, compared to 'model 7' (with no extra mechanical ventilation).

Sobhani et al., (2020) considered the potential of active free cooling Latent heat thermal energy storage (LHTES) to mitigate the cooling requirement of the passive house which may be subject to overheating in summer. LHTES systems use night cooling to provide solutions for sustainable cooling with the use of renewable cooling sources (Stockholm Chiu et al., 2013). Under the climate of Stockholm for which the scenario was not specified by the author, and through a multi-objective optimisation on cooling supply for various LHTES, the authors concluded that 75% of the cooling requirement could be met with the optimised LHTES.

Similar to the optimisation technique using NSGA-II (Andric et al., 2020), Mostafazadeh et al., (2023) introduce a novel simulation-based multi-objective optimisation approach by modifying the NSGA-III algorithm. This is the first proposed novel modified algorithm (prNSGA-III) to optimise active and passive energy retrofit measures under future climate change scenarios. Based on the optimised implemented retrofit measures (see Table 1f) of a residential building in Tehran, Iran, about up to 46% thermal discomfort can be reduced in the future climate scenario. The authors also emphasised the promising potential of the prNSGA-III in optimisation techniques for retrofit measures in other various future climate zones and scenarios. The multi-objective optimisation function of the prNSGA-III was formulated by the authors through the thermal comfort objective function as follows:

$$TDH = \frac{DOH}{OH} \times 100 \tag{13}$$

where TDH = thermal discomfort hours; DOH=annual discomfort hours; OH=occupied hours.

The multi-objective optimisation is thus:

$$[Maximise]F_1(x) = EP \tag{14}$$

$$[Maximise]F_2(x) = LCC \tag{15}$$

$$[Minimise]F_3(x) = TDH \tag{16}$$

Subject to:

$$x \in X$$

$$F_1(x) \geq EP_0 \tag{17}$$

$$F_3(x) \leq TDH_0 \tag{18}$$

where EP_0 and TDH_0 are environmental performance and thermal discomfort hours of the baseline building (representing the two core constraints of the multi-objective optimization); LCC is the life cycle cost; x is the vector of decision variables representing a specific retrofit strategy; and X is the feasible set of decision vectors.

For the above multi-objective pareto optimisation, the prNSGA-III developed by the authors operates such the best retrofit measures are selected to maximise the EP and LCC and to minimise the TDH.

Likewise, Luo and Oyedele (2022) deployed a novel hybrid-genetic algorithm and artificial neural network (GA-ANN) for optimisation purposes to select the optimal retrofit measures under changing future climate scenarios, implemented on two campus buildings (Northavon house and Q building) in Bristol, UK. The authors found that selected retrofit measures from current climate conditions may no longer work under future climate change scenarios, with at most 4.7% over estimation or 54.7% underestimation of energy, lifetime cost and carbon. Using the hybrid novel optimisation technique (GA-ANN), the authors recommended effective retrofit active and passive measures (see Table 1f).

Some studies reported the effectiveness of heat pumps, and the performance of some other active measures depending on the climate scenarios, for example, Rahif et al., (2022), conducted a time-integrated discomfort assessment for a base case of nearly zero energy dwelling, with no active free cooling in Brussels under current and future climate scenario. The authors first found that up to a 528% increase in overheating risk and about a 32% decrease in undercooling risk are projected by the end of the century. By comparing the performances of active systems, a reversible air-to-water heat pump (S02) could save HVAC energy consumption to about 6–13% compared to a gas-fired boiler + an air conditioner (S01). Secondly, the sensitivity analysis of the study showed that HVAC strategy, heating set-point, and cooling set-point are among the most influential parameters determining the HVAC primary energy use.

For the performance of active measure emission scenarios, Masi et al., (2021) conducted a sensitivity analysis by the use of modified weather files based on the representative concentration pathways (RCP) of the fifth assessment of the IPCC report, to determine the influence of climate change on photovoltaic productivity. The findings showed that climate change may bring an increase in the productivity of the photovoltaic from 3.3 KWp to 6.9 KWp peak power for the worst scenario emission, leading to a decrease in electricity demand from 28 to 17%. Similarly, Kharseh et al., (2015) investigated the impact of global climate change on the performance of GSHP systems in different climate zones (Stockholm, Doha, Istanbul). From the findings of the study, for a building with a standard thermal quality of building envelope (TQBE) as classified by the author, the GSHP annual energy consumption is projected to decrease by 5% (Stockholm) in cold climate and increase by 17.7% (Doha) in hot climate in 2050 compared to 2014. Equivalently, for a building with a low TQBE, the GSHP is projected to decrease by 8.5% in cold climates and increase by 18% in hot climates. Evidently, it can be said that the GCC has a significant impact on the performance of GSHP. This was also corroborated in the study by Shen and Lukes (2015), where the increase in global warming by 2–3 °C reduces the annual performance of GSHP in future climate scenarios for residential buildings, in the four USA cities under consideration. In fact, the study concluded that for this reason, there may be less competitiveness in the choice of GSHP in the future warming in the climate context of the USA.

4 Discussion

4.1 Analysis of studies and critique

From the previous section, it can be noticed that the number of studies dealing with effective climate adaptive or retrofitting or passive and active as well as renewable measures to the built environment, especially under different future climate scenarios, has increased from the past 5 years until 2023 compared to years that preceded. However, based on the summary in Table 1, one can notice that some studies only consider any effective measure under the Current Scenario (herein onward referred to as TMY), and even more studies failed to clearly specify whether any investigation was under TMY/Future Climate Scenario. TMY/Future Climate Scenario is herein onward referred to as TMY/FCS. Therefore, based on intuition, they are considered in such studies as 'Generic' in this paper.

It would be worthwhile to compare studies strictly on all effective active and passive measures based on reckoning (see Table 3) and currency (see Fig. 5). Although, other

Table 3 Categories of reports based on related measures and year of publication

Year	Passive	Active	Passive/Active	Ventilation related	PCM	Insulation related	Fenestration related	GRS/Cool roofs
2023	Pajek et al., (2022)	–	Mostafazadeh et al., (2023)	–	–	–	–	–
2022	Mehmood et al., (2022, Cui et al., (2022), Nunes and Giglio (2022), Solgi et al., (2017), Miri and Babakhani (2021), Pelletier and Calautit (2021), Wu et al., (2018), Zhao et al., (2019), Gallardo and Berardi (2022), Soudian and Berard (2019), Lingard (2021), Mahdy and Nikolopoulou (2014)	Ortiz et al., (2022), Italos et al., (2022), Kimiya Aram et al., (2022)	Gallardo and Berardi (2022), Zhou (2022), Luo and Oyedele (2022)	Mehmood et al., (2022), Cui et al., (2022), Nunes and Giglio (2022), Pelletier and Calautit (2021)	Vega et al., (2022), Gallardo and Berardi (2022), Zhou (2022), Al-Yasiri and Szabó (2022)	Calama-González et al., (2022), Guarda et al., (2019)	Mahmoud et al., (2022), Pajek et al., (2022)	Cascone (2022), Ortiz et al., (2022)

Table 3 (continued)

Year	Passive	Active	Passive/Active	Ventilation related	PCM	Insulation related	Fenestration related	GRS/Cool roofs
2021	Miri and Babakhani (2021), Ur Rehman et al., (2021), Hugo et al., (2021), Pajek and Košir (2021), Cirrincion et al., (2021)	Masi et al., (2021)	Heracleous et al., (2021)	Heracleous et al., (2021, Miri and Babakhani (2021)	Ur Rehman et al., (2021)	Hugo et al., (2021)	Pajek and Košir (2021)	Cirrincion et al., (2021)
2020	Andric et al., (2020), Laouadi et al., (2020), Zeinelabdein et al., (2020), Lingard (2021), Sabati et al., (2020)	Kolokotroni et al., (2013)	Liu et al., (2021), Efthymiou et al., (2020)	Laouadi et al., (2020)	Zeinelabdein et al., (2020)	Lingard (2021)	–	Andric et al., (2020), Sabati et al., (2020)
2019	Soudian and Berard (2019), Guarda et al., (2019), Sartor and Calmon (2019)	–	Zhao et al., (2019), Pokhrel et al., (2019)	–	Wu et al., (2018), Zhao et al., (2019)	Guarda et al., (2019)	–	Sartor and Calmon (2019), Pokhrel et al., (2019)

Table 3 (continued)

Year	Passive	Active	Passive/Active	Ventilation related	PCM	Insulation related	Fenestration related	GRS/Cool roofs
2018	Costanzoa et al., (2018), Lapisa et al., (2018), Wu et al., (2018), Thantonga et al., (2018), Mahdy and Nikolopoulou (2014)	Hyung An et al., (2018)	Andric et al., 2018)	Costanzoa et al., (2018), Lapisa et al., (2018)	Wu et al., (2018), Thantonga et al., (2018)	–	–	–
2017	Cardinale et al., (2013), Botti and Ramos (2017), Hamdy et al., (2017), Roetzel et al., (2013), Solgi et al., (2017)	–	Wang et al., (2017)	Botti and Ramos (2017), Hamdy et al., (2017), Solgi et al., (2017), Wang et al., (2017)	Rahimpoura et al., (2017)	Pierangioli et al., (2017)	–	–
2016	Saffari et al., (2016), Chernousov & Chan, 2016)	–	–	–	Saffari et al., (2016), Chernousov and Chan (2016)	–	–	–
2015	Yildiz (2015), Meng et al., (2015), Sajjadian et al., (2015)	Kharseh et al., (2015), Shen and Lukes (2015)	–	Yildiz (2015)	Meng et al., (2015), Sajjadian et al., (2015)	–	–	–
2014	Roetzel et al., (2013), Hooff et al., (2014), Mahdy and Nikolopoulou (2014)	–	–	Roetzel et al., (2013), Hooff et al., (2014)	–	–	Mahdy and Nikolopoulou (2014)	–

Table 3 (continued)

Year	Passive	Active	Passive/Active	Ventilation related	PCM	Insulation related	Fenestration related	GRS/Cool roofs
2013	Kolokotroni et al., (2013)	Sobhani et al., (2020)	–	–	–	–	–	Kolokotroni et al., (2013)
	45	9	11	16	15	6	4	8

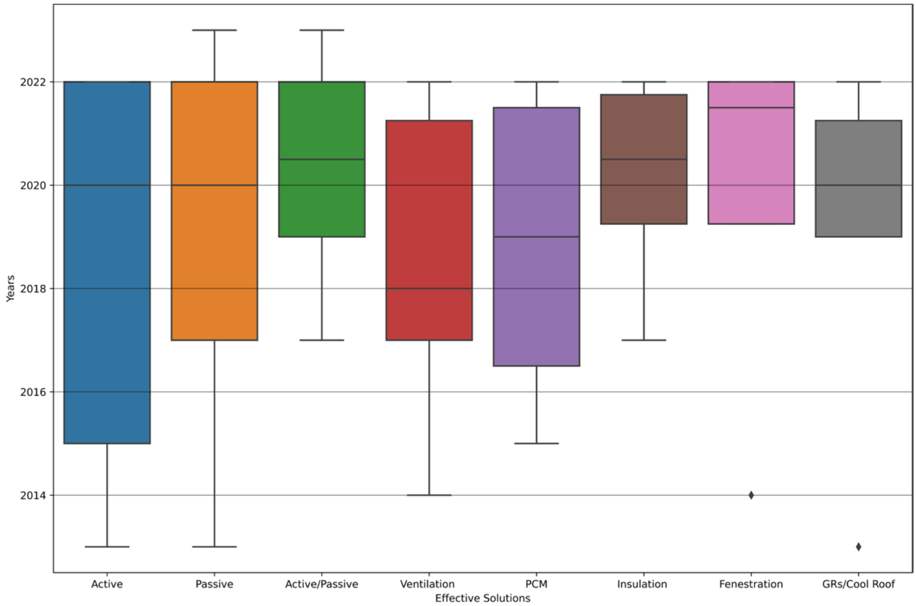

Fig. 5 Boxplot showing effective solutions against the year of publication

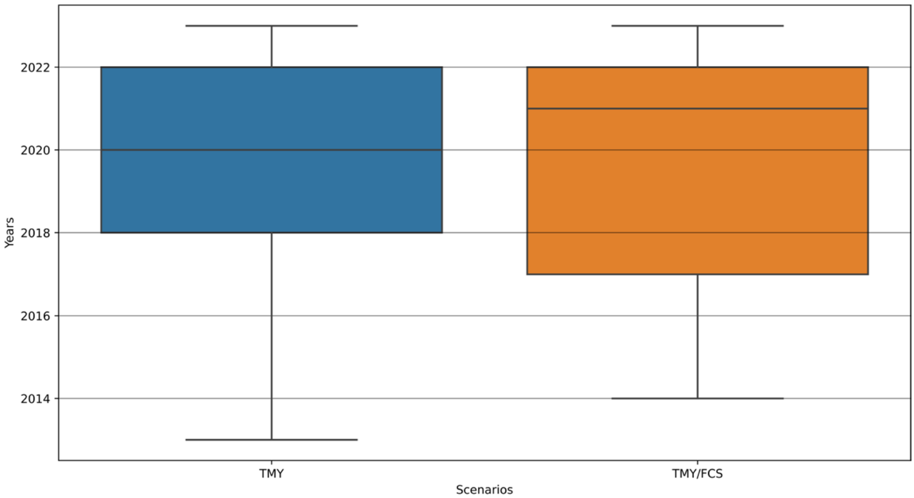

Fig. 6 Boxplot showing studies based on climate scenarios against the year of publication

studies were a combination of any active and passive measures. Again, with reference to Fig. 5, it is important to clarify that ventilation means it was the most sensitive passive measure against any other passive measure combined with it in the papers, thereby, the category was simply termed ventilation in the figure. This was a similar case with PCM, insulation, fenestration and GRs/cool roofs in the same figure. For simplicity, the Generic climate studies are merged with the MTY studies in Fig. 6. By comparison of these studies to similar ones, impacts of climate adaptive measures could be very much extended under the TMY/FCS but were not. For example, while some studies relating to measures on ventilation effectiveness and overheating comprehensively projected the impacts and sensitivity of these measures under the TMY/FCS (Andric et al., 2018, 2019, 2020; Cui et al., 2022; Díaz-Lopez & Serrano-Jiménez et al., 2022; Fereidani et al., 2021; Mehmood et al., 2022; Nair et al., 2022; Ozarisoy & Altan, 2021; Perez-Andreu et al., 2018; Rañeses et al., 2021; Soaresa et al., 2017; Zhou et al., 2020a, 2020b), others were only restricted to the TMY or the Generic climate (Andric et al., 2018, 2020; Cui et al., 2022; Díaz-Lopez & Serrano-Jiménez et al., xxxx; Fereidani et al., 2021; Nunes & Giglio, 2022; Perez-Andreu et al., 2018; Zhou et al., 2020a). Similarly, for studies relating to PCM (or PCM in combination with other measures) and their impacts on energy savings, only one study (Meng et al., 2015) comprehensively considered the TMY/FCS, although, the year of the study was in 2015 (the study clearly shown in the boxplot in Fig. 5), while the remaining PCM related studies reported, only considered the TMY or any Generic climate (Botti & Ramos, 2017; Costanzoa et al., 2018; Hamdy et al., 2017; Heracleous et al., 2021; Hooff et al., 2014; Laouadi et al., 2020; Lapisa et al., 2018; Miri & Babakhani, 2021; Pelletier & Calautit, 2021; Roetzel et al., 2013; Sandaruwan et al., 2022; Solgi et al., 2017; Ur Rehman et al., 2021; Wang et al., 2017; Yildiz, 2015).

This means that more comprehensive studies on the impacts of PCM under future emission scenarios are lacking and could be explored. Again, among studies relating to insulations plus other climate adaptive measures, only (Edenhofer et al., 2014; Saffari et al., 2016; Zeinelabdein et al., 2020) considered the TMY/FCS while their Counterpart (Chernousov & Chan, 2016; Faccani et al., 2017; Wu et al., 2018) only considered the TMY or any Generic climate. Other studies combined effective measures as either ventilation through fenestrations (windows) plus any other measure(s), thermal transmittance of fenestrations plus any other measure(s), or shading devices of fenestrations plus any other measure(s). Three of these studies (Gallardo & Berardi, 2022; Vega et al., 2022; Zhou, 2022), considered the TMY/FCS while only a study (Zhao et al., 2019) was based on the TMY. On effective measures pertaining GRs or albedos of cool roofs, only three studies (Al-Yasiri & Szabó, 2022; Lingard, 2021; Toe & Kubota, 2015) were done under TMY/FCS, and the others (Thantonga et al., 2018; Calama-González et al., 2022; Guarda et al., 2019; Sajjadian et al., 2015; Soudian & Berard, 2019) under just the TMY. Some most recent studies have shown rewards of emerging optimisation techniques (Bayesian Bootstrap, NSGA-II, prNSGA-III, GA-ANN, MBC) to optimising adaptive passive/actives under TMY/FCS (Andric et al., 2020; Cirrincion et al., 2021; Kolokotroni et al., 2013; Pokhrel et al., 2019; Rañeses et al., 2021), although one study only considered the TMY (Hugo et al., 2021). To the best of our knowledge, there is yet any study on the robustness of Model Predictive Control (MPC) in optimising any climate adaptive measures (for example, innovative involutions and PCM) based on future climate scenarios. This emerging field of optimisation techniques could be explored further.

5 Conclusion and area of future study

This paper started by re-emphasising the glaring threats of the future warming climate scenarios through evidence from the recent IPCC reports. After, it reviewed up-to-date reports on effective active and passive solutions to mitigate such threats from past studies. The following are the key conclusions of this paper:

i. By geography, there is a paucity of studies in Africa within the scope of this paper, with only three reports recorded (Hooff et al., 2014; Vega et al., 2022; Zeinelabdein et al., 2020). This could potentially be an area to look into in future research.
ii. Among the EU and UK papers with Mediterranean to oceanic and temperate climates, for both housing dwellings and commercial buildings, the most effective solutions are natural ventilation/ventilative cooling. In almost all cases of these instances, future climate scenarios were considered.
iii. In subtropical to hot regions in Asia, the most effective solution is the PCM in public buildings. However, not all the papers fully considered the future climate scenarios.
iv. In most of the Middle-East regions with semi-arid to arid climates, ventilation/wind-catchers and PV are the most effective solutions. While some considered the future climate scenarios, others do not.
v. In different regions across the US and Canada for both public buildings and households, the most effective solutions are any exterior shading, low E double glass, PCM and reflective roof. Only future climate scenarios are discussed in these regions.
vi. In South American regions, the notable effective solutions are Insulation, envelope thermal capacity and ventilation and PCM, with few studies having focused on future climate scenarios.
vii. Among the papers on Australia having a sub-tropical to hot-humid climate, the notable most effective solutions are green roofs for office buildings and PCM for residential buildings. However, none considered the future climate scenario.

This paper only utilizes data from the Scopus database, future research could expand the database using the same method.

Data availability The data used to support the findings of this study are included within the article.

Declarations

Conflict of interest The author declare that they have no conflict of interest.

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