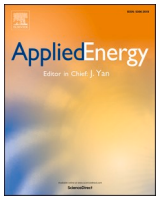
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Resilient cooling pathway for extremely hot climates in southern Asia

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HIGHLIGHTS

- Parametric analysis of resilient cooling solutions in an extremely hot region.
- Evaluation of synergies & trade-offs with regard to energy savings and comfort hours.
- Night ventilation and solar protection provide the highest synergies.
- Insulation and airtightness without improved ventilation provide important trade-offs.
- Ventilation and higher thermostat settings are key points toward resilience.

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ABSTRACT

Global warming is increasing extreme heat conditions, with existing energy efficiency policies showing trade-offs between mitigation objectives and adaptation to climate change. This research aims to identify the best resilient cooling solutions that should be promoted in the built environment of extremely hot countries to increase their heat resilience capacity. The impact of climate change on climate zones, cooling thermal demand (kWh/m^2), and indoor heat discomfort hours (DH_h, hours) in buildings is evaluated in different extremely hot dry climates of southern Asia through a parametric analysis for 2020, 2050 and 2080 under the A2 (medium–high) emission scenario. Then, cooling alternatives with higher synergies and trade-offs between energy efficiency (energy consumption) and resiliency to extreme heat (passive survivability) are highlighted. TRNSYS simulation software and ASHRAE criteria were used to characterise climate zones and calculate buildings' cooling needs and discomfort hours. Pakistan, in southern Asia, was selected as a hot reference region characterised by various climatic regions. The simulated scenario shows how Pakistan's extremely hot dry climate surface may increase from 36.9 % to 78.1 % by 2080, increasing annual cooling needs ranging from 20.56 to 66.96 kWh/m^2 and indoor discomfort hours ranging from 423 to 1267 h. The results demonstrate how the passive solutions with higher synergies between energy savings and indoor comfort hours are, in decreasing order, ventilative cooling, reflective and ventilated roofs, shading in windows, and roof insulation. They can provide energy savings ranging from 13.1 to 7.1 kWh/m^2 while reducing indoor discomfort by 320 to 131 h for extremely hot climates. Moreover, the sufficiency action related to higher thermostat settings, from 24 to 25 °C to 25–26.5 °C, was the most effective strategy to decrease energy demand. Additionally, there are trade-offs between energy-saving and heat resilience with highly insulated alternatives when ventilation is not adequately addressed. Despite increasing energy savings by 14.4 kWh/m^2, discomfort hours are increased by 256 hours when air conditioning is unavailable, increasing building overheating by 5.1 %.

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Nomenclature

0B	extremely hot dry climate zone
1B	very hot dry climate zone
2B	hot dry climate zone
3B	warm dry climate zone
ASHRAE	American Society of Heating Refrigeration and Air conditioning Engineers
A2	medium–high emission scenario
ACH	air change rate, h^{-1}
CDD	cooling degree days
CV-RMSE	coefficient of variation of root mean square error
DH	discomfort hours
GCMs	global climate models
GHG	greenhouse gas emissions
GIS	geographic information system
HDD	heating degree days
IPCC	Intergovernmental panel on climate change
NMBE	normalized mean bias error
RCM	regional climate model
R^2	coefficient of determination
T	Temperature, ℃

Subscripts

b	base
cu	upper comfortable
h	heat
m	monthly
op	operative
out	outdoor
t	time in hours

Superscript

n	number of hours
max	maximum
min	minimum

1. Introduction

This research highlights the best resilient cooling strategies that should be promoted in the built environment of extremely hot countries to mitigate the impact of climate change. The target is to highlight those measures that should be promoted in future building regulations to increase the heat resilience capacity of the building stock.

Climate change is causing increased frequency and intensity of heatwaves, with irreversible changes in morbidity (e.g., dehydration, heat stroke and heat exhaustion) and mortality [1,2]. This is driving an unprecedented increase in cooling demand, increasing greenhouse gas (GHG) emissions and further contributing to climate change. Today, space cooling accounts for the highest share of energy in the building sector in hot countries [3]. Globally, it is expected that energy demand for cooling will more than triplicate by 2050 [4]. Actions in building stock are required to increase the heat resilience of cities and mitigate climate risk, above all in extremely hot regions.

Many studies have addressed the influence of climate change on the built environment. However, existing findings still present some limitations related to the indicators considered, locations studied, methods applied, and weather data used. They are further detailed in the following paragraphs.

Firstly, previous studies, and even existing policies, are highly focused on indicators to mitigate energy consumption in heating and cooling, and their associated GHG emissions, not promoting adaptation to climate change [5,6]. Less attention has been given to the impact of climate change on the passive survivability of buildings. For example, Masi et al. [7] assessed different refurbishment designs for residential buildings. They found that the most profitable solution is the application of cool paint for roofs, installing selective windows, external shading and the insulation of opaque envelopes to reduce cooling load. Sivanand et al. [8] investigated the retrofitting of double glazing solutions for maximum energy savings. They found that combining a solar film with retrofit double glazing reduces the annual HVAC energy consumption by up to 20 %. Invidiata et al. [9] showed how low absorptance, thermal insulation, and solar shading could reduce up to 50 % of the future cooling and heating load of a typical residential building in Brazil. Bambrook et al.[10] simulated a simple house in Sydney, showing that reduced infiltration, controlled ventilation, lower window U values and better insulation of walls and roof could reduce up to 94 % of heating and cooling load. Harkouss et al.[11] investigated optimal passive design for residential buildings in twenty-five different climates to reduce energy demand for heating and cooling. Their result showed that the optimal combination of envelope passive design parameters led to significant cooling load savings compared to the base case, reaching up to 87 % in Kunming, 54 % in Dakar and 52 % in Barentsburg, respectively. A similar study was conducted by Usman et al. [12] to find out the energy-efficient building envelope in twenty-four different locations. Maucec et al. [13] studied the building performance in three different locations in Europe and showed that building shading and set point temperature have the most significant impact on energy needs.

In the context of climate change in extremely hot areas, the passive survivability and heat resilience of buildings should be prioritised beyond energy efficiency and carbon metrics since most homes do not have or lack access to air conditioner (AC). Heat resilience is understood as " the ability of buildings to meet the occupant's needs and provide for a safe, steady and comfortable use in response to changing conditions outside" [14]. According to IEA [15], out of the 44 % of the world's population living in a hot climate, only 12 % own an AC. Around 1.1 billion people worldwide lack access to cooling systems that protect them from intense heat. In these cases, Ren et al. [16] showed that unreasonable search for energy efficiency measures such as increased insulation and airtightness might jeopardise a building's ability to maintain comfortable thermal conditions during heatwaves. Additionally, the continuous electricity supply for these hot regions in the peak summer season is a big challenge. In particular, in Pakistan, 30 % of people do not have access to electricity [17], while the rest receive an intermittent supply of electricity with a daily load shedding of 6 to 8 h. This situation of energy rationing could be worse under climate change [18]. Thus, for these regions adversely affected by climate change [19,20], building design should be based on synergies between air-conditioned and unconditioned scenarios, considering the passive survivability of the built environment.

Secondly, a considerable number of studies on a wide range of geographies, including Europe, North and South America, East Asia and Australia, are available with a focus on evaluating the heating and cooling load as climate change metrics [21–27]. However, less attention has been given to the extremely hot regions of South Asia, South-East Asia or Sub Saharan Africa, where six hundred thirty million people are most at risk. They live in substandard housing on low incomes with limited, intermittent, or insecure access to electricity and limited electrical access to cooling appliances. The impact of climate change on the thermal performance of buildings is different in these parts of the world [28,29], and according to recent IPPC climate change projections, South Asia shows that warming is likely to be above the global mean [30].

Thirdly, regarding the method used to evaluate climate change impacts, most studies focus on using the degree-day method to evaluate the impact of climate change in buildings, which supposes a direct

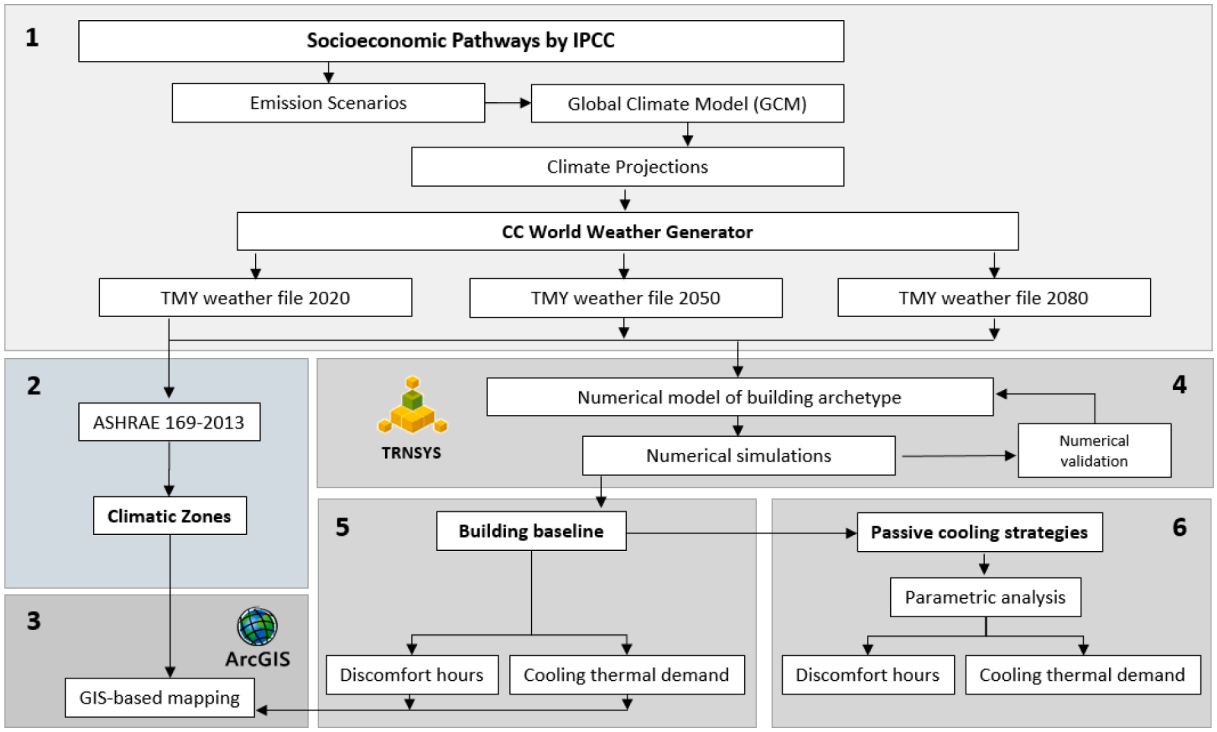


Fig. 1. Conceptual framework to analyse the impact of climate change in extremely hot regions.

approximation to determine the impact of climate change on heating and cooling demand. For instance, Ramon et al. [31] calculated future cooling degree days (CDD) for Belgium under a high emission scenario and found that CDD will increase by 2.4 times by this century. Olonscheck et al. [32] used the degree-day method in Germany and showed that heating energy consumption would decrease by 44–75 % while cooling energy consumption will increase by 28–59 % in residential buildings. Spinoni et al. [33] investigated the impact of climate change on residential buildings in Europe and showed that energy demand for cooling will increase, particularly in the Mediterranean region and the Balkans. However, it should be considered that humidity, building characteristics and solar radiation are not considered in the degree-day method. This fact leads to significant deviations compared to real cooling needs [34]. Thus, the real climate change impact may be overlooked.

The use of dynamic methods based on hourly energy simulation tools does not have these limitations. Moreover, it may provide additional insights by combining metrics to measure the passive survivability of buildings in these extremely hot regions. However, again, most studies have focused on developed countries using energy metrics. Ciancio et al. [35] simulated a typical residential building to investigate the impact of climate change on 19 different cities in Europe and found that the Mediterranean basin will suffer more than other European areas. In Turkey [36] and Qatar [36], the cooling load for the air-conditioned building will increase due to more frequent and longer heatwaves with greater intensity. Asimakopoulous et al. [36] investigated future heating and cooling loads for residential, commercial and educational buildings in 13 different climate zones of Greece and found that cooling demand would increase by 248 % under the A2 scenario of IPCC by the end of this century. Wang et al. [37] created weather files for 2020, 2050 and 2080 and investigated the cooling and heating energy use in 15 USA cities located in seven climatic zones for an office building. They found that energy use will increase in zone 1 to 4 while it will decrease in zone 6 and 7. Similarly, a study in Florida showed an increase in cooling demand for commercial buildings between 26 % and 80 % by 2100 [38]. Pilli-Sihvola et al. [39] analysed the performance of residential and commercial buildings in five European countries: Finland, Germany, Holland, France and Spain, and found the energy consumption for cooling will increase more in South Europe than in North and Central Europe.

Fourthly, existing studies to support building design are usually supported by using typical meteorological weather files based on historical data [5,40,41], which supposes another constraint to promote heat resilience in the built environment. Several studies demonstrate that low-energy cooling solutions that operate well today may not perform well in the future or during extreme occurrences like heat waves or power outages. Wang et al. [42] examined the nationwide impact of climate change on building energy use in the United States of America. They concluded that by the 2080 s, passive cooling would be unsuitable for some cities, including San Diego, due to global warming. Osman et al. [43] investigated the climate-responsive building design strategies for Sudan from 2015 to 2070. They found that by 2070, the natural ventilation and active heating strategies will be no longer beneficial. Therefore, attention should also be given to building design concerning projected weather climates instead of historical or current weather conditions.

These four limitations related to indicators considered, locations studied, methods applied, and weather data used should be tackled to support a sustainable and resilient cooling pathway in extremely hot regions where a fifth of humanity lives. Research efforts are required to assess and identify the best resilient cooling pathway that should be promoted in extremely hot regions, using indicators to measure the passive survivability of the built environment through accurate dynamic simulation methods and considering future weather scenarios.

1.1. Objectives and novelty:

This research aims to evaluate the climate change impact through scenario A2 (medium–high emission scenario of IPCC) in extremely hot regions to identify optimal passive cooling strategies that should be promoted to improve the resilience capacity of the built environment. Pakistan, in southern Asia, was selected as a hot reference region characterised by various representative climatic regions, and the scope was limited to the residential sector. First, current climate zoning in the

region was evaluated following ASHRAE standard 169 classification criteria. Second, the climate change impact on climate zoning and building performance was evaluated. A dynamic simulation through a validated archetype building model in TRNSYS was used to calculate indicators based on energy consumption (with AC systems) and passive performance (free-running conditions). ASHRAE adaptive comfort model was used to characterised the passive survivability of the building through discomfort hours. Finally, a parametric analysis of resilient cooling alternatives through different climate regions for 2020, 2050 and 2080 was carried out in order to highlight synergies and trade-offs between energy indicators and passive survivability metrics.

Pakistan was selected for this study since it is adversely affected by climate change [44], and represents an extremely hot area of South Asia (a region home to one-fifth of humanity) with no previous studies, where close to 28 % of households are considered to be in fuel poverty, with families spending more than 10 % of their income on energy and struggling to afford cooling [45]. This situation has significant adverse impacts on Pakistani families' health [46], and it is even worse at lower latitudes [47], where temperatures are higher.

The following novel research contributions are provided in this study to support the challenges mentioned above.

- Optimal resilient cooling measures that should be promoted in future building regulations of extremely hot regions are highlighted in order to support the decision-making process to mitigate climate impact and improve the resilient capacity of the built environment.
- Additionally, the climate zoning of Pakistan is provided under current and future weather conditions following ASHRAE standard 169 [48]. It also involves the impact of climate change on thermal cooling needs and heat discomfort hours, showing existing vulnerabilities and climate risks in the region.

The paper is structured as follows. Section 2 describes the materials and methods employed in creating future weather files, climatic zoning, and numerical model for thermal energy needs and discomfort hours. Section 3 provides discussion and results. It is divided into three sections: evaluation of climate zones in Pakistan under climate change scenario, the impact of climate change in discomfort hours and thermal cooling demand, and the role of different resilient cooling alternatives to mitigate the impact of climate change. Finally, limitations and conclusions are drawn in sections 4 and 5, respectively.

2. Materials and methods

The conceptual framework employed in this research is shown in Fig. 1, which is divided into the following sections:

1-Climate scenarios. Creation of future weather files (Section 2.1), using the CCWorldWeatherGen tool to generate weather files for the (TMY2) typical meteorological years 2010–2040 (named 2020), 2041–2070 (named 2050), and 2071–2100 (named 2080).
2-Classification of climatic zones. Evaluation of climate zones for Pakistan according to ASHRAE thermal zone criteria 169 and its variation under the impact of climate change (Section 2.2).
3-GIS-based mapping. Development of GIS-based map for climate zones (Section 2.3).
4-Numerical model of building archetype. Definition and validation of a reference building simulation model using TRNSYS (Section 2.4).
5-Building baseline. Evaluation of thermal cooling energy needs and heat discomfort hours for a typical residential building across the climates of Pakistan (Section 2.5).
6-Mitigation and adaptation measures. Parametric study to investigate the role of different adaptation strategies in reducing thermal energy needs and heat discomfort hours in different climatic zones (section 2.6).

2.1. Climate scenarios

Emissions scenarios defined by the Intergovernmental Panel on Climate change (IPCC) are used as input for Global Climate Models (GCMs), the most complex quantitative models for forecasting climate change. GCMs are a mathematical model of the general circulation of a planetary atmosphere. They simulate how the atmosphere, ocean, and land surface interact and predict the changes in the Earth's climate over time. GCM models predict metrological parameters with monthly average values at different altitudes with 100–200 km resolution. Regional Climate Models (RCM) are used to downscale this prediction to a 25 to 50 km resolution.

GCM and RCM model provides monthly average data, which is insufficient for building simulation tools (hourly weather data is required). The morphing technique [49] is then used to add projected monthly changes to historical hourly weather files to generate future weather files. In this study, Climate Change World Weather File Generator (CCWorldWeatherGen) [50,51] is used to create future weather files. This software was developed by the Sustainable Energy Research Group at the University of Southampton [52]. The tool is freely available and has enabled many studies on climate change impacts [35,9,38]. This Microsoft Excel-based tool was created to generate future TMY2 (typical meteorological year) weather files for any location in the world under the A2 (medium–high) emissions scenario over three-time slices, the 2020 s, 2050 s, and 2080 s. This software transforms base climate typical meteorological weather files to "climate change" weather files using a "morphing algorithm" considering the HadCM3 GCM model under emission scenario A2. A2 refers to medium–high emission scenarios of AR4 (fourth assessment report of IPCC). This scenario considers the continuous increase of global population, regional economic disparities and diversified society, focusing less on rapid economic growth. The baseline weather data was derived from [53].

The morphing method used in CCWorldWeatherGen was developed by Belcher et al. [49]. It consists of three parts; shift, stretch, and/or a combination of both.

i) a 'shift' of the current hourly weather file parameter by adding the predicted monthly mean temperature (obtained from the GCM). Mathematically, this can be written as Eq. (1).

$$S_i^{'} = S_i + \Delta i_m \tag{1}$$

where $S_i^{'}$ is the future weather file parameter, S_i is the current weather file and Δi_m is the monthly predicted change.

To convert the monthly average changes to an 8,760 hourly prediction, monthly changes are multiplied by the number of hours in the corresponding month.

ii) a 'stretch' of the current hourly weather file parameter by scaling it with predicted monthly mean temperature (obtained from GCM). It is defined by Eq. (2).

$$S_i^{'} = S_i a_m \tag{2}$$

where a_m is the fractional monthly change.

iii) a combination of a 'shift 'and a 'stretch' for the current hourly weather file. It is shown in Eq.(3).

$$S_i^{'} = S_i + \Delta i_m + a_m(S_i - (S_i)_m) \tag{3}$$

where $(S_i)_m$ is the monthly mean temperature of the current hourly weather file.

Further details on the CCWorldWeatherGen can be found in reference [49].

2.2. Classification of climatic zones

Climate zone classification was developed using ASHRAE-169

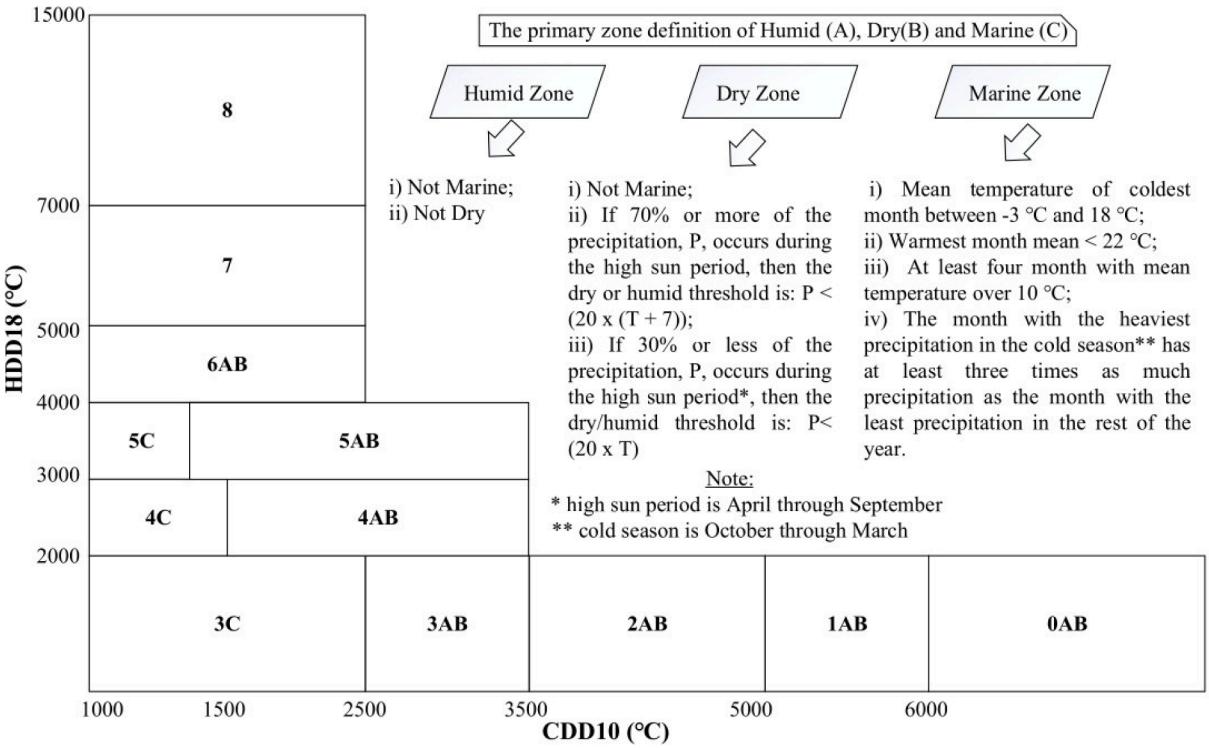


Fig. 2. Thermal and primary zone definition according to ASHRAE 169.

criteria, considering temperature, precipitation, cooling, and heating degree days. This step involves the pre-processing of weather files generated with CCWorldWeatherGen (section 2.1) for different cities in Pakistan; and the calculation of required variables such as monthly average temperature, average yearly temperature, monthly average precipitation, cooling and heating degree days at a base temperature of 10 and 18 ℃, respectively.

Eq. (4) was used for the calculation of cooling degree days (CDD) and Eq. (5) for heating degree days (HDD).

$$CDD = \sum_{k=1}^{365}\left[\left(\frac{T_k^{max} + T_k^{min}}{2}\right) - T_b\right] \quad (4)$$

$$HDD = \sum_{k=1}^{365}\left[T_b - \left(\frac{T_k^{max} + T_k^{min}}{2}\right)\right] \quad (5)$$

Where Tk^{max} is daily the maximum outdoor air temperatures, Tk^{min} is the daily minimum outdoor air temperatures, and T_b is the base temperature in ℃.

Climate zones are defined in ASHRAE 169 using two indicators: a number and a letter. The number represents the thermal zone, and can range between 0 and 8 depending on the CDD and HDD at a base temperature of 10 °C and 18 °C, respectively. The number 0 shows extremely hot climate, number 1 (very hot), 2 (hot), 3 (warm), 4 (mixed), 5 (cool), 6 (cold), 7 (very cold) and 8 (subarctic/arctic). The letter designates the primary zone, which may be humid (A), dry (B), or marine (C). The definition of the primary (letter), thermal (number) and integrated zones (number and a letter) are shown in Fig. 2.

The primary zones were calculated based on the criteria mentioned in Fig. 2. First, the marine was evaluated, then the dry zone and the remaining regions were classified as the humid zone. Second, thermal zones were defined by calculating cooling and heating degree days according to the criteria shown in Fig. 2. Finally, primary and thermal zones were integrated and were shown with a number and a letter.

2.3. GIS-based mapping

A geographic information system (GIS) was used to manage, analyse and map the available climate information. More specifically, ArcGIS software ArcMap 10.8 was used to carry out geostatistical interpolations of the different variables that define the ASHRAE climate zones, as well as to link the results to each of Pakistan's regions. The methodological workflow is shown in Fig. 3.

First, the ASHRAE primary zones were obtained by interpolation. Since these primary zones are based on multiple variables, only two classes (dry and humid zones) were found for Pakistan. Pakistan does not have a marine zone, so they were interpolated as binary variables. Second, the ASHRAE thermal zones, CDD10 were spatially interpolated. None of the data points reached 2000 HDD18, meaning they were not relevant for differentiating these thermal zones. Finally, the results obtained for the thermal and primary zones were associated with the Pakistan district delimitation using spatial geostatistics, thus calculating the mean values for each region.

The interpolation was conducted using ordinary kriging with a spherical variogram, which was selected after validating its performance with cross-validation. Kriging is a widely used technique in environmental science studies focusing on regionalised variables such as rainfall [54,55], temperatures [55–57], or derived variables such as HDD and CDD [58–61]. This stochastic interpolation technique has also proven to yield better results than other deterministic approaches, such as the Inverse Distance Weighting [62,63].

From the intersection between primary and thermal zones, the ASHRAE climate zones are obtained. These were then associated with an administrative delimitation using zonal statistics, which helps estimate a unique reference value for a spatially-distributed variable within a certain domain. The combination of geospatial interpolation techniques with zonal statistics is a common practice when associating data points to a real distribution, usually corresponding to a particular administrative delimitation that might contain other types of information [64]. This logic has been followed, among others, by the USA International Energy Conservation Code when defining the climate zone maps based

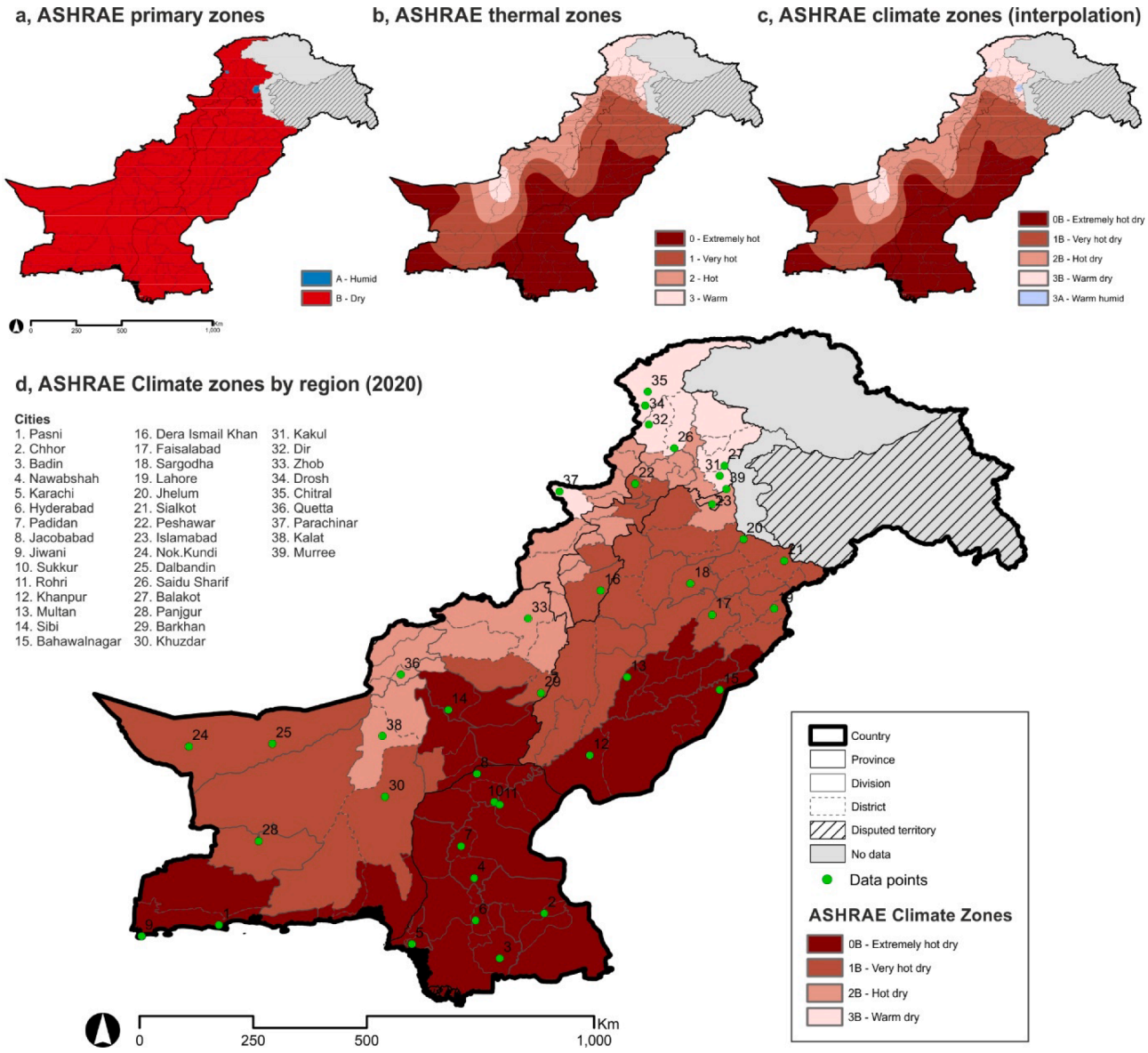


Fig. 3. The methodology employed for climatic zoning following ASHRAE 169 criteria and using ArcGIS software.

on ASHRAE for the United States at the county level [65].

In this study, climate zones are estimated at the district level to enhance their potential utility for local administrations, which will be able to associate this classification with other socio-demographic variables. Results are obtained for all the Pakistan regions, except the Centrally Administered Areas of Azad Kashmir and Gilgit Baltistan, the disputed regions in the northeast. These regions were excluded due to the absence of climatic data and the significant altitude differences, which discouraged extending the interpolation to these regions.

This procedure was carried out both for the current climate scenario (the year 2020, see Fig. 3) and for the future climate scenarios of 2050 and 2080. It was also used to represent the spatial variability of discomfort hours and cooling energy demand derived from the numerical modelling of a reference building archetype. This modelling is further explained in the following sections.

2.4. Numerical model of building archetype

The numerical model was developed in the simulation software TRNSYS (Trnsys System Simulation) v18.2, widely used by researchers to model and simulate the transient behaviour of energy systems [66]. This software solves differential equations generated from the system configuration with the modified Euler method and uses a successive iteration method to solve the non-linear equations for each component. The TRNSYS model library has built-in components for calculating thermal loads, ventilation, air conditioning systems, and data files, making it suitable for calculating cooling loads and indoor thermal comfort.

The flow diagram for the numerical simulation model is shown in Fig. 4, while the process flowsheet developed for this study is shown in Fig. 5. First, the building archetype is defined in SketchUp. The geometric model is then imported in TRNSYS TRNBuild v3.0 to include building envelope characteristics (walls, windows, roof), internal gains (light, equipment, and occupants), and their variability over time. TRNBuild generates a "*.b18″ file, used in the multi-zone building Type56 in the TRNSYS simulation studio. TRNSYS simulation studio reads and processes the input file (like the weather file and *.b18 file generated from TRNBuild), iteratively solves the system and plots the system variables. In the TRNSYS simulation studio, a typical weather file of different cities of Pakistan generated from the CCWeatherGen tool, as described in section 2.1, was implemented using the standard weather data reader component (TYPE 15–3) for the calculation of thermal loads

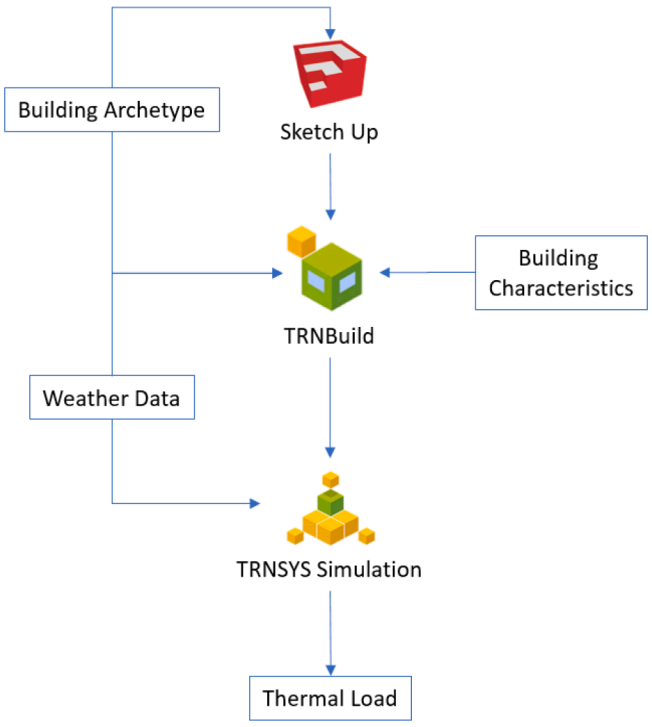


Fig. 4. Flow diagram for numerical model.

and heat discomfort hours of the different cities for the years 2020, 2050 and 2080.

2.4.1. Building archetype

A typical two-story multi-family building was selected as a case study, which is representative of the conventional construction of multi-family dwellings in Pakistan. The reference building is a representative case of building stock. The building archetype has a total gross floor area of 250 m^2 and consists of two bedrooms, a living room, a drawing-room, a kitchen and two bathrooms per floor. According to Pakistan Social & Living Standards Measurement Survey [67], 70 % of the houses in urban areas are double story having 2 to 5 bedrooms. The geometry floor plan of the building archetype is shown in Fig. 6.

Clay bricks and concrete are common materials for constructing walls and roofs in urban areas of Pakistan [68], and a cement layer is used on both sides of walls. The main parameters of building fabric are shown in Table 1.

Internal gains due to occupancy are considered as follows: two occupants in each bedroom from 10 pm to 7 am, two people in the living room from noon to 4 pm, and four people from 4 pm to 10 pm were assumed. Gains were considered 125 W for occupants in the living room and 80 W for bedrooms, according to EN 13799. Heat gains from lights and equipment were related to the reference floor area as 2 W/m^2 and 3 W/m^2 (value recommended for a multi-family house based on SIA 2024). Thermal bridges were considered at 0.1 W/m^2K of envelope area [69]. The total internal thermal mass of the building was considered by multiplying the internal heat capacity of indoor air volume by a constant of 3 [70]. Type 77 (ground temperature model) was used to model the heat transfer from the floor to the soil. Solar absorptance values for façade and walls were kept at 0.5 and 0.65. Two ventilation profiles are considered: one air change rate (ACH) of the building's leaking area, and another ACH due to window openings. Infiltration leakage was defined by an ACH value of 1.2 h^{-1}, a value recommended for multi-family with medium–high leakage levels according to the procedure reported in Annexe B of EN 15242:2007 [71]. Natural ventilation was defined by an ACH value of 2 h^{-1}. The ventilation profile via windows is controlled according to the difference between indoor and outdoor temperatures to ensure it only happens when the outdoor temperature is less than the zone temperature.

2.4.2. Model calibration and validation

The numerical model was validated using the criteria specified in ASHRAE Guideline 14–2014 [72]. The Normalized Mean Bias Error (NMBE), the Coefficient of Variation of the Root Mean Square Error (CV-RMSE), and the coefficient of determination (R^2) are the uncertainty indices used for model validation. NMBE is a normalisation of the MBE index used to scale and produce comparable results; CV-RMSE quantifies the error variability between measured and simulated values, and R^2 quantifies how near simulated values are to the regression line of measured values. According to the ASHRAE Guideline, a simulation model should have an NMBE of less than 5 % and a CV-RMSE of less than 15 % compared to monthly calibration data. Additionally, a value of R^2 greater than 0.75 is recommended.

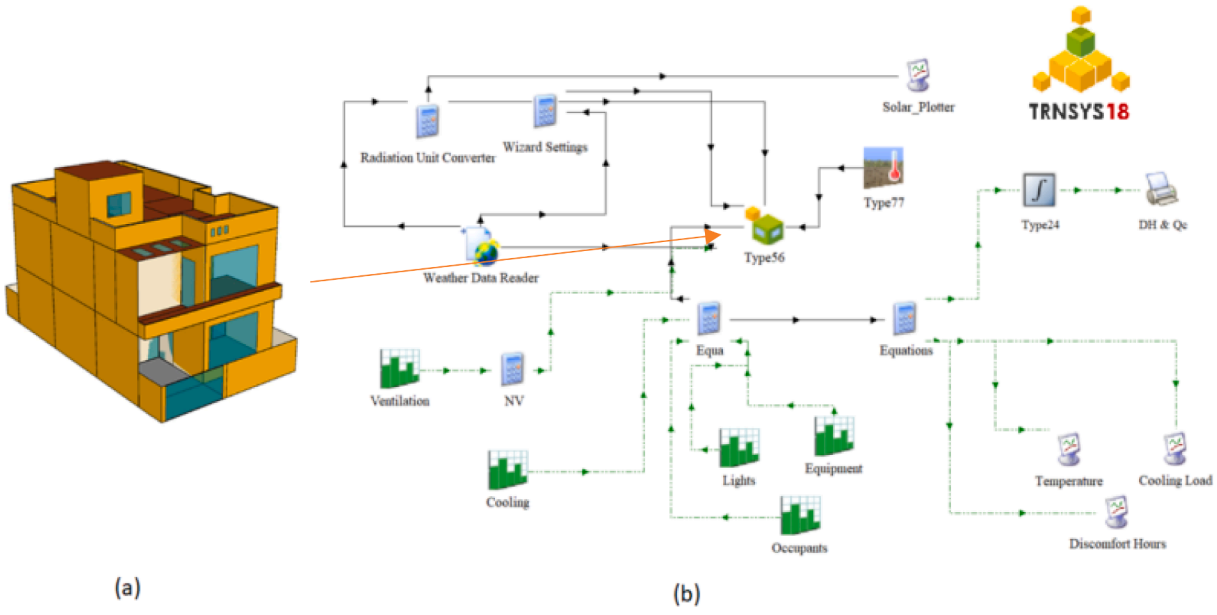


Fig. 5. (a) SketchUp model of the reference building; (b) Process flowsheet of the numerical simulation model developed in TRNSYS v18.

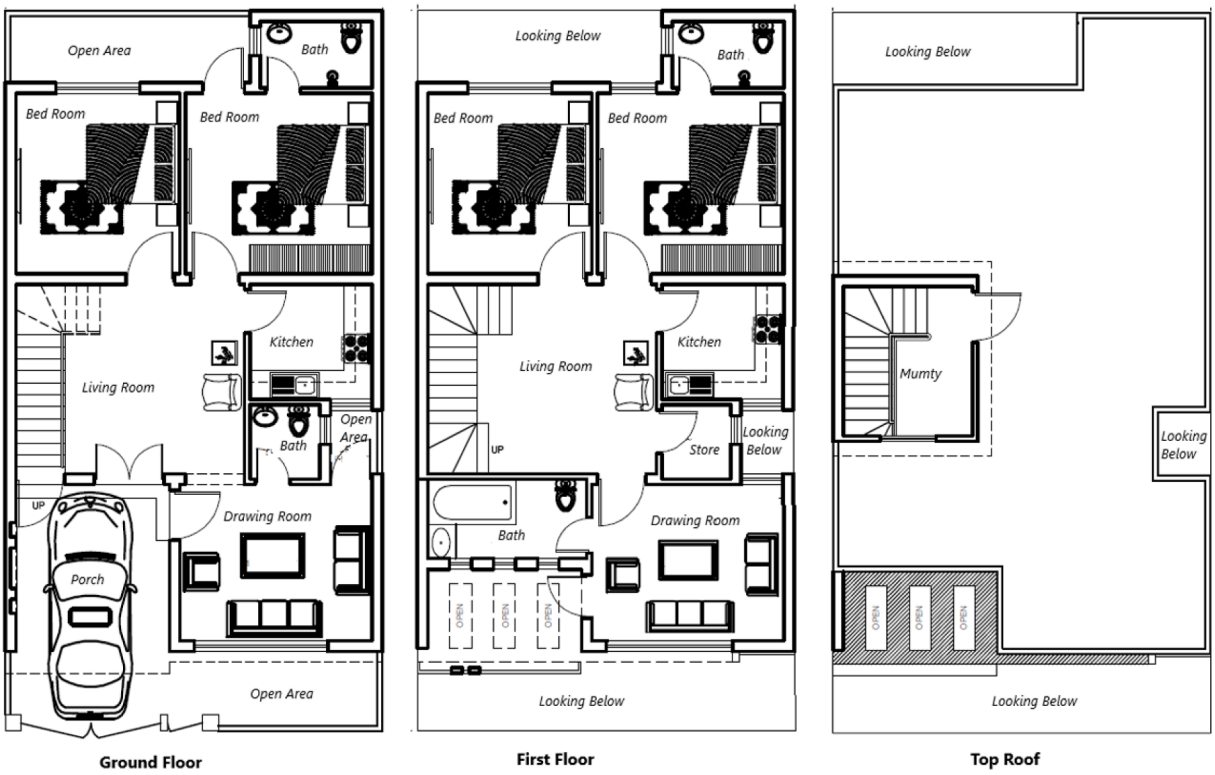


Fig. 6. Geometry plan of the selected building archetype.

Table 1
Characteristics of the building elements of the reference building model.

Element	Definition	Characterization
Windows	Single glazed window with aluminum frames	U-value:5.72 W/m^2 K
Façade	Cement mortar,solid burnt clay bricks, cement mortar	U-value:2.19 W/m^2 K
Roof	Cement mortar,concrete, bitumen, mud Phuska, roof tiles	U-value:2.02 W/m^2 K
Floor	Soil, sand, brick masonry (clinker), plain cement concrete, ceramic tiles	U-value: 0.7 W/m^2 K
Internal walls	Cement mortar, solid burnt clay bricks, cement mortar	U-value:2.92 W/m^2 K

In this study, the building model was calibrated with monthly energy data using a reference case in Lahore. Measured cooling energy demand was compared with simulated values through an iterative calibration process by modifying uncertain parameters until convergence of simulated and measured values, as shown in Fig. 7.

The comparison of measured and simulated values showed an NMBE of 3.3 %, a CV-RMSE of 9.1 %, and an R^2 of 0.9, meeting the requirements of ASHRAE standard 14–2014 [72].

2.5. Building baseline

The building baseline was characterised in different regions of Pakistan using two building performance indicators: thermal cooling energy needs (kWh/m^2) using an idealised cooling system for air-conditioned buildings and annual heat discomfort hours (DH_h, hours) in free-running buildings.

The thermal cooling demand (kWh/m^2) was calculated using design conditions fixed at 24 ℃ in the daytime, 25 ℃ at night, and an absolute humidity ratio of 14 g per kg of air.

Heat discomfort hours (DH_h, hours) represent the number of hours in a year when the operative temperature (Top) lies above the upper comfortable temperature limit (T_{cu}). The adaptive comfort model ASHRAE 55–2017 [44] was used to determine heat discomfort hours for different cities of Pakistan for a typical free-running residential building (absence of mechanical heating or cooling system).

The following equation was used to determine the upper limit (T_{cu}) of the comfort range (80% acceptability limit) [73].

$$T_{cu} = 0.31\, f(T_{out}) + 21.31 \tag{6}$$

where $f(T_{out})$ is the prevailing mean outdoor air temperature in ASHRAE 55 for 2017. The following relation is used to calculate the prevailing mean outdoor air temperature [74].

$$f(T_{out}) = (1-\partial).\left[Te.(d-1) + \partial.Te(d-2) + \partial^2.Te(d-3) + \partial^4.Te(d-4) + \cdots\right] \tag{7}$$

where ∂ is a constant having value of 0.6. Te(d-1) is the daily mean air temperature of outdoor air at a time 'd' of a series of equal intervals (days). Equation (8) calculates the annual heat discomfort hours.

$$DH_h = \sum_{t=0}^{t=n} \Delta t \quad if\ Top > T_{cu} \tag{8}$$

Where n is the number of hours in a year (8760).

2.6. Mitigation and adaptation measures

Mitigation and adaptation are two types of climate change responses. Mitigation strategies refer to measures that mitigate the contribution to climate change, primarily reducing energy consumption and associated environmental impact in the built environment. On the other hand, adaptation is based on measures to mitigate the effects or consequences of climate change. Both targets may include the same portfolio of solutions based on energy conservation strategies in buildings. However, while mitigation exclusively focuses on energy and carbon targets and metrics to address the root cause of the problem, adaptation refers to

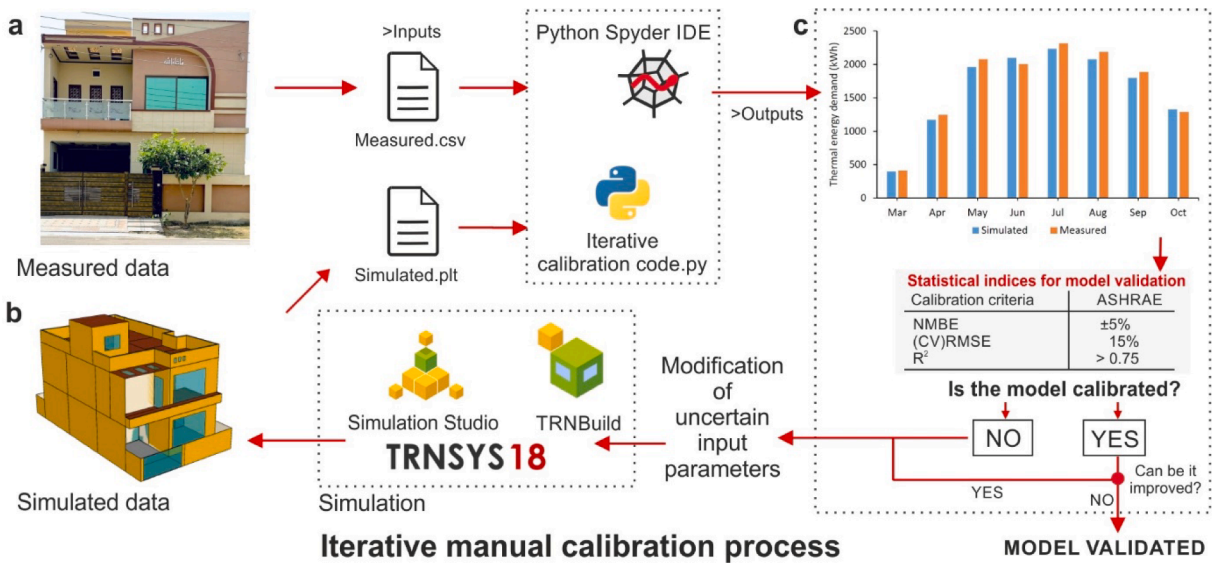


Fig. 7. Iterative manual calibration workflow for model validation. a, Dwelling real photo. b, Numerical building model in TRNSYS. c, Results of python script after each simulation interaction, providing the statistical indices to verify the model accuracy and validate the model.

Table 2
Breakdown of the individual passive measures to improve building performance.

Code	Passive Measures	Base Case Value	Retrofitting target
Building structure			
M1	Insulation of roof	U-value: 2.02 W/m^2·K	U-value: 0.44 W/m^2·K
M2	Insulation of exterior walls	U-value: 2.19 W/m^2·K	U-value: 0.8 W/m^2·K
M3	Insulation of windows	U-value: 5.7 W/m^2·K	U-value: 4 W/m^2·K
Thermal bridges			
M4	Default allowance per envelope area	Htb: 0.10 W/m^{2}K	Htb: 0.05 W/m^{2}K
Solar properties to mitigate solar heat gains			
M5	Shading reduction factor due to external shading devices	SRF: 0.8	SRF: 0.4
M6	Solar factor of windows	g-value: 0.84	g-value: 0.63
M7	Internal blinds	No	Yes
M8	Solar absorptance of roof	ab: 0.65	ab: 0.25
M9	Solar absorptance of exterior walls	ab: 0.5	ab: 0.25
Internal gains (internal heat gains)			
M10	Heat flow rate of lighting	2.0 W/m^2	Reduced by 20 %
M11	Heat flow rate of appliances	3.0 W/m^2	Reduced by 20 %
Ventilation and air infiltration			
M12	Air change rate (ACH) of infiltration	ACH: 1.2 h^{-1}	0.6 h^{-1}
M13	Night ventilation	ACH: 2 h^{-1}	5 h^{-1}
Operating conditions			
M14	Set-point temperature	Day: 24 °C Night: 25 °C	Day: 25 °C Night: 26.5 °C

dealing with its effects on health and well-being, using, for example, comfort metrics. As a result, synergies and trade-offs may be found when comparing solutions.

Table 2 sumarises the list of individual passive measures proposed to evaluate synergies and trade-offs betweeen the mitigation and adaptation pathway of the building stock.

Solutions are divided into six sections, comprising solutions for improving insulation in the building structure, reducing thermal bridges, reducing solar heat gains, mitigating internal heat gains, improving ventilation and air infiltration patterns, and lowering operating conditions in the case of AC systems. The latter addresses efforts to reduce energy demand through sufficiency by reducing people's basic needs by implementing changes in thermostat settings. Measures are evaluated considering metrics to assess their mitigation potential (thermal cooling demand) or adaptation capacity (discomfort hours in free-running conditions).

The values of retrofitting targets defined in Table 2 were proposed according to the Pakistan building code [75], literature review, and other technical handbooks, reports and standards [76–78]. For instance, the solar absorptance of a surface determines the fraction of incoming short-wave radiation absorbed. Common values for brick walls and concrete roofs in the built environment are 0.65 and 0.5, respectively [79]. A target value of 0.25 was proposed according to recent short-wave absorptivity values from the literature [79]. Natural ventilation through window opening was assumed to have an ACH of 2 h^{-1} in the baseline scenario. In the target scenario, it is assumed that ventilation is addressed through an appropriate building design, achieving an ACH of 5 h^{-1} when the indoor temperature is above the outdoor temperature and higher than 24 °C.

3. Results and discussion

The optimal passive cooling strategies that should be promoted to improve the resilience capacity of the built environment in extremely hot regions are analysed and discussed in three sections. Firstly, the impact of climate change in the climate zones of Pakistan is analysed. Secondly, thermal energy needs and comfort conditions inside buildings under changing climate conditions are shown and discussed. Finally, the synergies and trade-offs of different passive cooling alternatives to improve building performance under climate change scenarios were evaluated from the point of view of air-conditioned buildings and free-running conditions.

3.1. Impact of climate change in climate zones of Pakistan

The impact of climate change on the climate zones of Pakistan through spatial maps for 2020, 2050 and 2080 are shown in Fig. 8. The study was conducted assuming the most representative climate zone per district. A total of 127 districts were investigated. Additionally, Fig. 9 shows the change of territorial surface per each climatic zone throughout the years.

The results of climate analysis in 2020 show how Pakistan has four thermal climatic zones. Extremely hot dry climate zone (0B), very hot dry climate zone (1B), hot dry climate zone (2B) and warm dry climate zone (3B). The extremely hot dry climate zone (0B) is the largest climate

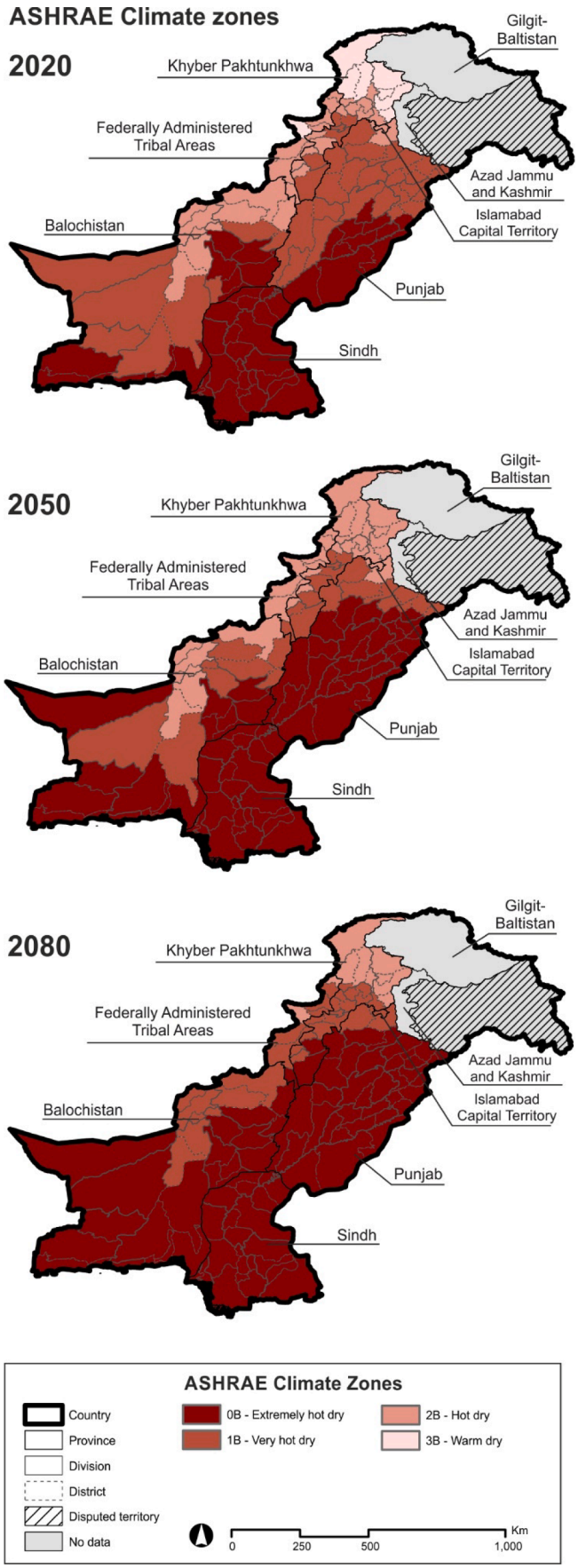


Fig. 8. Climatic zones of Pakistan for years (a) 2020, (b) 2050 and (c) 2080.

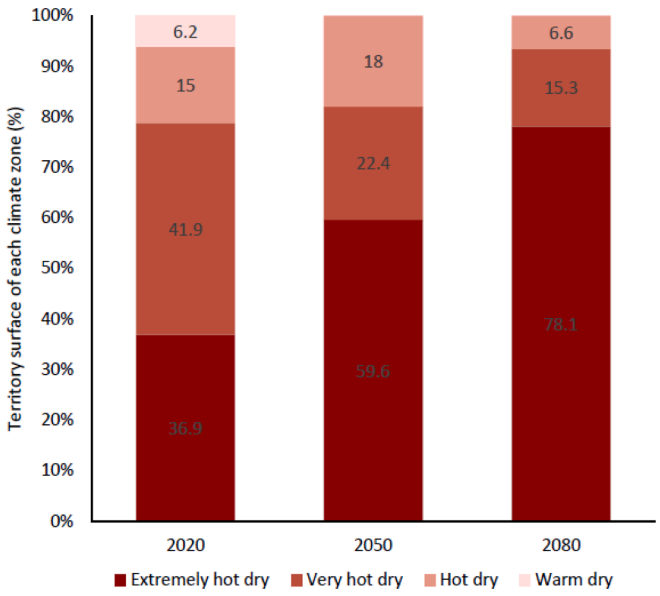


Fig. 9. Territory surface per climate zone by 2020, 2050 and 2080.

Table 3
Number of districts per climate zone in 2020, 2050 and 2080.

	2020	2050 (changes from 2020)	2080 (changes from 2020)
3B – Warm dry	8	0 (+0)	0 (+0)
2B – Hot dry	30	32 (+2)	10 (−20)
1B – Very hot dry	40	27 (−13)	31 (-9)
0B – Extremely hot dry	49	68 (+19)	86 (+37)

zone covering 36.9% of the territory (49 districts). Southern Punjab, Sindh and some areas of Balochistan are located in this climate zone. More than half of the population lives in Punjab, while one-fourth of the total population lives in Sindh [80], and under the impact of climate change, these people will be adversely affected. At the same time, very hot dry climate (1B) and hot dry climate (2B) occupy 41.9% (40 districts) and 15% (30 districts) of the evaluated territory surface, respectively. The areas such as north Punjab, central Punjab, and most Balochistan areas lie in a very hot climate zone. However, upland areas of Balochistan, such as Quetta and most of Khyber Pakhtunkhwa, are located in the hot climate zone. The northern regions of Pakistan, located at high latitudes, have a warm climatic zone. The warm dry zone (3B) has the lowest percentage of territory surface and will only be observed at 6.2% of the territory surface (8 districts).

The results of climate analysis in 2050 and 2080 show that the percentage of territory surface with an extremely hot dry climate zone is dramatically increasing throughout the years, moving from 36% of territory by 2020 to cover 59.6% by 2050 and 78.1% by 2080. By 2080, the entire Sindh province and more than two-thirds of the Punjab province territory surface will lie in an extremely hot climate zone. Additionally, the warm dry climatic zone (3B) will vanish by 2050.

The analysis shows that all districts would move towards warmer thermal zones under the medium–high emission scenario evaluated. No district would change their climate towards colder conditions. The number of districts per climate zone and projections is summarised in Table 3. It is important to note that 49 districts are already based on an extremely hot dry climate zone (0B), the highest level of climate zone classification, and will not change their climate zone. Out of the rest of the districts, it is calculated that by 2050, 34 districts will shift one climatic zone, either from warm to hot, or hot to very hot or very hot to extremely hot. By 2080, a total of 86 districts would be extremely hot

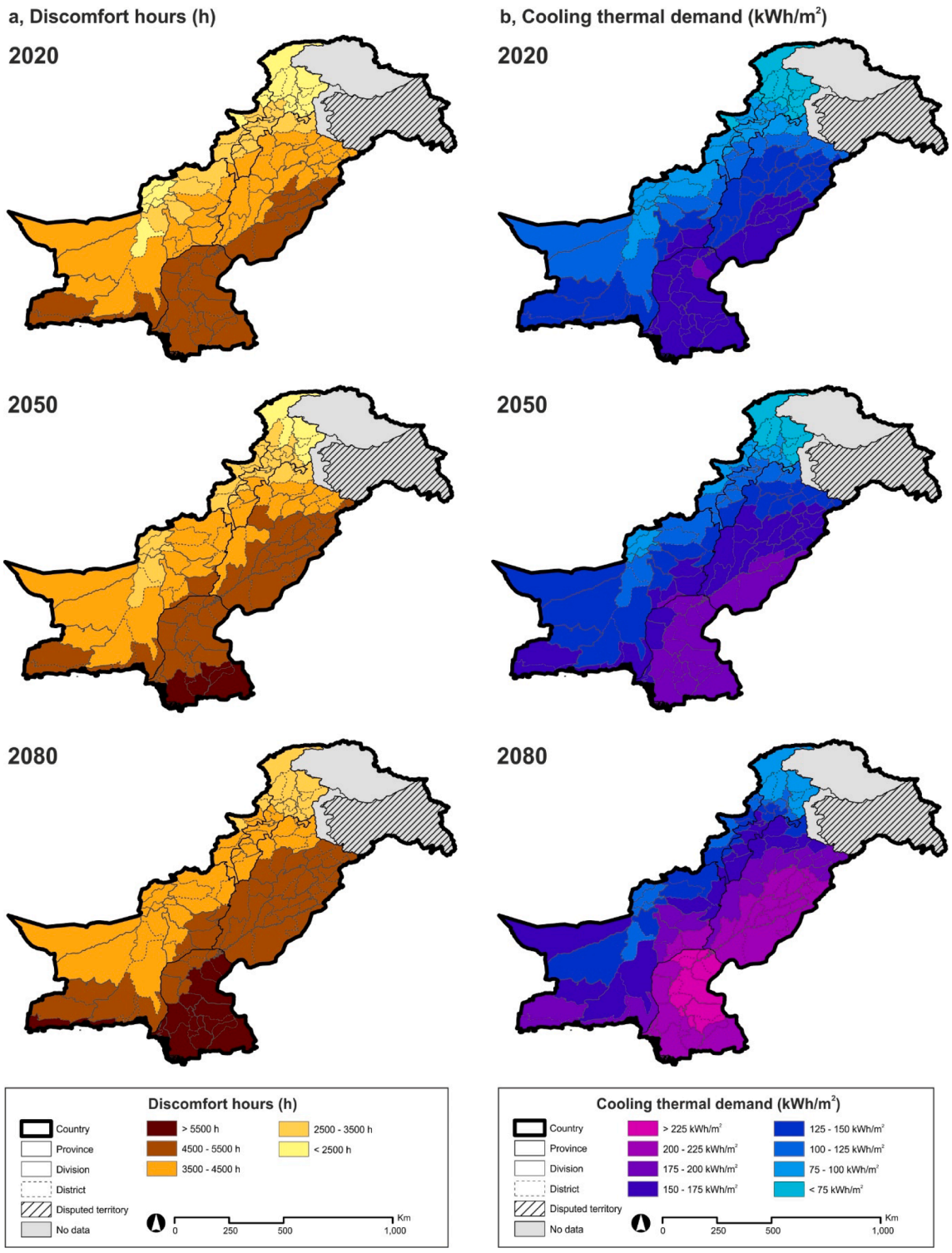


Fig. 10. Spatial maps of discomfort hours (a) and thermal energy needs for cooling (b) in different years.

dry climate zone (0B) under these climate change projections.

The analyses confirm that thermal climate zones would change significantly over the years under these climate change projections, and the climatic classification for 2020 may not be applicable in the whole country by 2050 and 2080.

3.2. Impact of climate change on discomfort hours and thermal cooling demand

The spatial distribution of discomfort hours (a) and annual thermal energy needs for cooling (b) is shown in Fig. 10.

Based on hourly cooling demand for 2020, Pakistan can be divided into six categories. The first category, which has the lowest energy needs

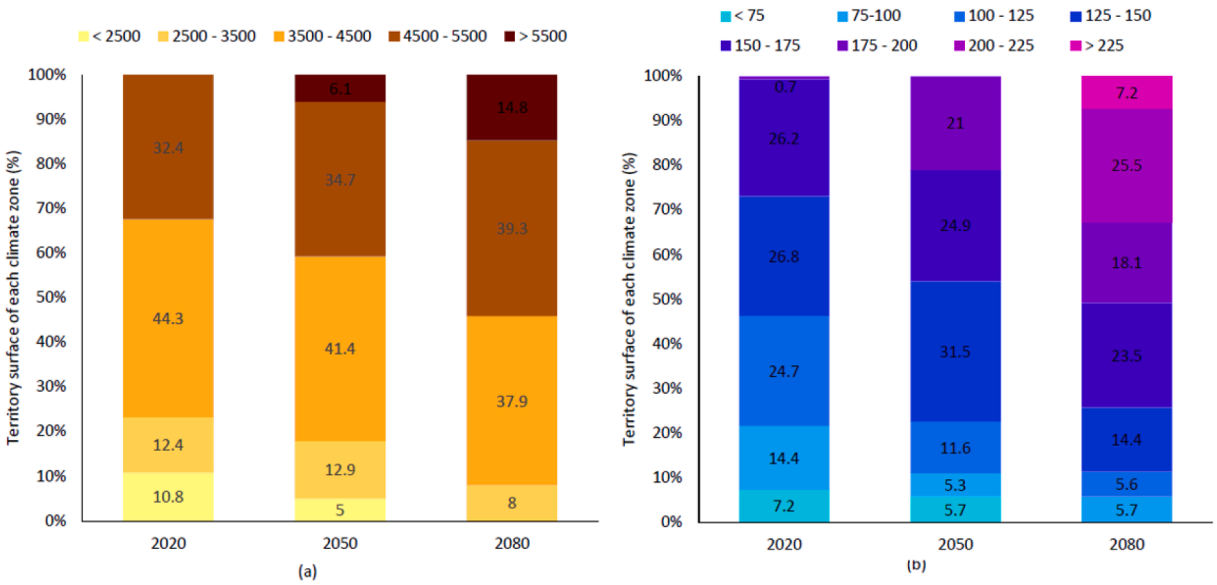


Fig. 11. Territory surface of each category in 2020, 2050 and 2080; (a) annual heat discomfort hour (b) annual thermal energy demand for cooling (kWh/m^2).

for cooling due to high latitude, is located in the north of Pakistan (most areas of Khyber Pakhtunkhwa province) and have thermal energy needs of less than 75 kWh/m^2. The second category includes southern parts of Khyber Pakhtunkhwa province and the uplands of Balochistan. These regions need thermal energy demand of 75–100 kWh/m^2. The energy demand in plain areas of Balochistan, including districts like Nok Khundi and Panjur and some areas of north Punjab, lies in the third category. The energy demand in these regions is 100–125 kWh/m^2. The areas of central and north Punjab and the foothills of Balochistan have an energy demand of 125–150 kWh/m^2 and lie in the fourth region. The southern regions of Punjab and most areas of the Sindh province lie in the fifth category and have thermal energy demand for cooling in the range of 150–175 kWh/m^2. The highest energy demand for cooling in 2020 (175–200 kWh/m^2) is needed in the north region of Sindh, such as Sukkur and surrounding districts. It can be seen from Fig. 10 that these regions are shifting towards higher thermal energy demand categories over the years. Based on yearly discomfort hours for 2020, Pakistan can be divided into five categories. The first category has the lowest heat discomfort hours due to high latitude, is located in the north of Pakistan (most areas of Khyber Pakhtunkhwa province) and has annual heat discomfort hours of less than 2500. The most vulnerable areas in terms of heat discomfort hours are almost the entire province of Sindh and southern Punjab. The annual heat discomfort hours in these areas are above 5500.

It is important to note that a maximum number of heat discomfort hours do not mean maximum cooling energy requirements. Discomfort hours in this study are when operative temperature lies above the upper threshold values of the comfort range. However, it does not consider how far or near it is from the upper limit of comfort range. That is why some cities that slightly lie above the upper limit of comfort criteria could have less energy demand for cooling than cities whose discomfort hours lie pretty far from the comfort range. The hourly simulations in TRNSYS show that maximum cooling energy requirements were found in Sukkur (175.4 kWh/m^2) in Sindh for 2020, while maximum heat discomfort hours are registered in Badin, Sindh (5282). This cooling energy demand under climate change will increase to 197.3 kWh/m^2 and 240.59 kWh/m^2 by 2050 and 2080. Similarly, these heat discomfort hours will increase to 5544 and 5952 by 2050 and 2080, respectively. On the other hand, minimum thermal energy requirements for cooling and minimum heat discomfort hours were found in Chitral (53.9 kWh/m^2) and Abbottabad (1873) in 2020. This city's energy demand for cooling will increase to 67.57 and 91.26 kWh/m^2 by 2050 and 2080, respectively. Likewise, this city's heat discomfort hours will increase to 2413 and 2976 by 2050 and 2080. The overall average cooling energy demand of the whole country is 123.3 kWh/m^2 in 2020, and this will increase to 141.7 kWh/m^2 (+14.9%) and 175.4 kWh/m^2 (+42.3%) by 2050 and 2080, respectively. The overall average heat discomfort hours of the whole country are 3862 in 2020, and this will increase to 4155 (+7.6%) and 4619 (+19.6%) by 2050 and 2080, respectively.

The percentage of the Pakistan territory occupied by each category of the annual heat discomfort hours and thermal energy demand for cooling is shown in Fig. 11.

The result shows that in 2020, approximately-one-fifth of the territory surface had annual heat discomfort hours of less than 3500, while 32.4% of the territory surface had more than 4500 h. Due to climate change, more regions are getting hotter, and the percentage of territory surface of heat discomfort hours below 3500 decreases to 17.9% and 8% by 2050 and 2080, respectively. On the other hand, the surface of the country with heat discomfort hours above 4500 increases to 40.8% and 54.1% by 2050 and 2080, respectively. Similarly, the result shows that in 2020, 21.6% of the territory surface has thermal energy demand lower than 100 kWh/m^2, while less than 1% of the territory surface has more than 175 kWh/m^2. Because of the effects of climate change, more regions are getting hotter, and the percentage of territory surface with cooling demand under 100 kWh/m^2 decreases to 10.8% and 5.7% by 2050 and 2080, respectively. At the same time, the percentage of territory surface with cooling demand higher than 175 kWh/m^2 is increasing to 21% and 50.8% by 2050 and 2080, respectively.

3.3. Resilient cooling alternatives toward mitigation and adaptation

This section assesses and identifies the best resilient cooling alternatives that should be promoted in the built environment to meet mitigation and adaptation targets. Three cities from three different climate zones were chosen to identify the solutions with higher synergies between energy efficiency (energy consumption) and heat resiliency (passive survivability):

- Sukkur: it represents the extremely hot climate zone. It is the third-largest city in the Sindh province, and has peak temperatures that exceed 50 ℃ in summer.
- Lahore: it represents the very hot climate zone. It is Pakistan's 2nd most populated city, home to more than 12 million people, and capital of Pakistan's most populated province (Punjab).

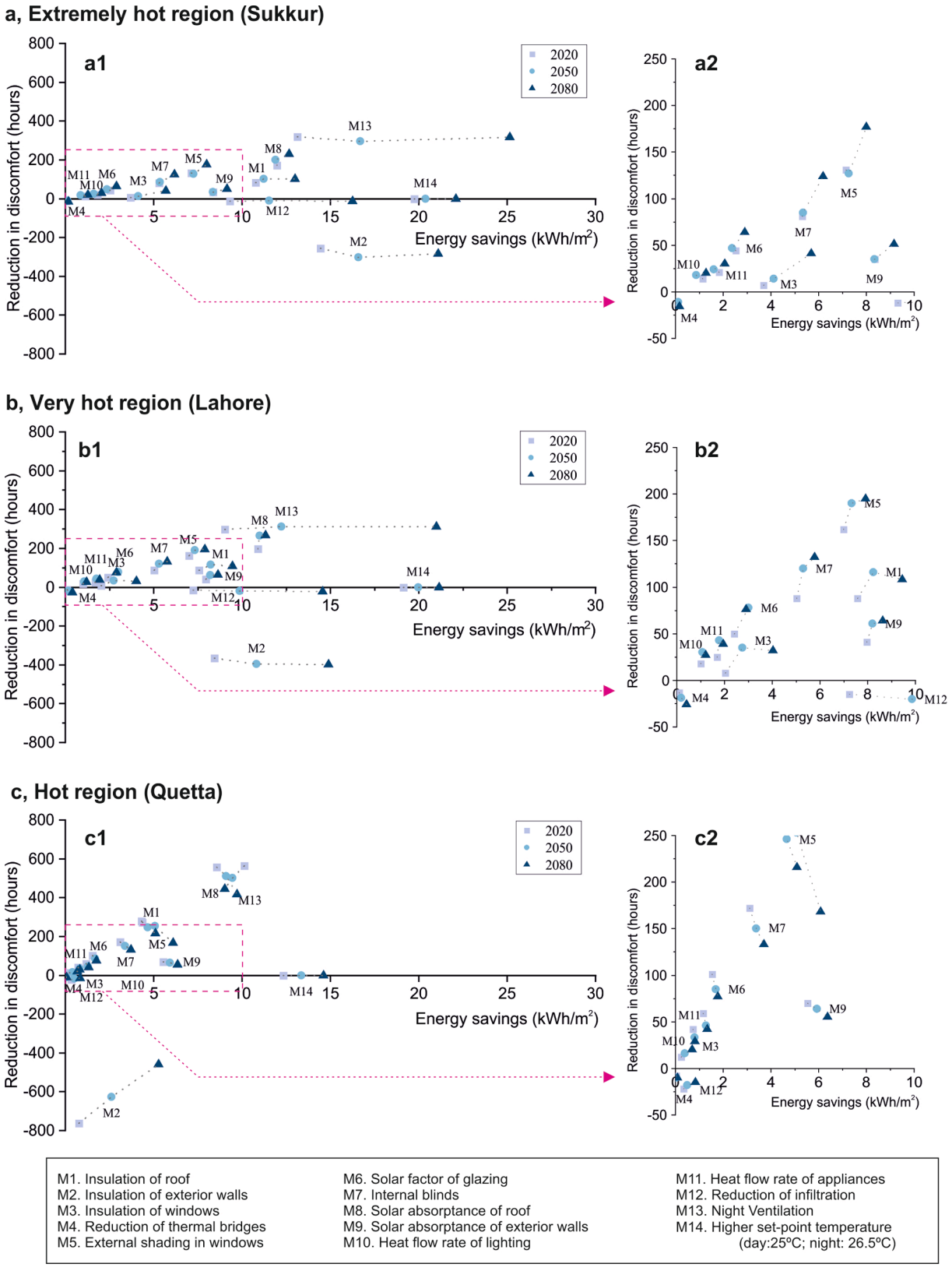


Fig. 12. Effect of passive cooling solutions on energy savings (kWh/m^2) and reduction of discomfort hours. Left side: All measures, Right side: zoom view.

- Quetta: it represents the hot climate zone. It is the capital of Balochistan province.

The results of different passive measures for the three aforementioned cities are presented in Fig. 12 and are tabulated in appendix. The x-axis shows the potential of energy saving in air-conditioned buildings compared to the baseline scenario (in kWh/m^2). The y-axis shows the reduction of indoor discomfort hours in free-running conditions (in hours) obtained through the ASHRAE adaptive comfort model.

The result shows that night ventilation (M13), the solar absorptance of the roof (M8), external shading of windows (M5) and roof insulation (M1) are passive cooling measures with high synergy in energy savings and reduction of discomfort hours, in all the investigated climate zones. These passive measures can provide energy savings ranging from 13.1 to 7.1 kWh/m^2 while reducing discomfort hours from 320 to 131 h for extremely hot regions. For very hot regions (Lahore) and hot regions (Quetta), these measures provide energy savings ranging from 10.9 to 7.0 kWh/m^2 and 10.1 to 4.3 kWh/m^2. Similarly, these measures reduce discomfort hours in the range of 297 to 162 h and 564 to 280 h for very hot and hot regions.

Heat dissipation through natural ventilation (M13) is highlighted as the most effective solution to reduce energy demand and increase comfort. Ventilative cooling provides the highest synergy to meet mitigation and adaptation targets. For extremely hot climates, this measure reduces up to 319 (6.36%) discomfort hours and cooling demand by 13.13 kWh/m^2. Similarly, for very hot climates and hot climates, this measure reduces discomfort by 297 and 564 h along with energy savings of 9.02 and 10.12 kWh/m^2, respectively. The results also show that the ventilation potential to improve building thermal performance is decreasing over the years. The possible reason for this is climate change, increasing the average temperature. For example, in Quetta, the ventilation measure reduces only 20.6% (502 h) and 14.3% (445 h) from the base discomfort hours of 2050 and 2080. Similar trends are found in Lahore and Sukkur. In Lahore, the potential of ventilation measures is seen at 6.37% and 5.79%, respectively, for the years 2050 and 2080. In Sukkur, this reduced to 5.67% and 5.65% by 2050 and 2080, respectively.

The reduction of solar gains in the opaque surface, above all in the roof (M8), is highlighted as the second-best alternative to reduce indoor overheating. It can be addressed by implementing ventilated and/or reflective surfaces on roofs. Existing roofs in Pakistan are primarily constructed flat using reinforced cement concrete (RCC) slabs. The findings indicate that low solar absorptance in the building roofs can efficiently minimise solar gains and thus mitigate discomfort hours. For instance, in Quetta, discomfort hours were reduced by 557 (29.49%) with low solar absorptance. In Lahore and Sukkur, this measure reduces discomfort hours by 198 (2.3%) and 171 (1.9%) hours.

The reduction of solar gains through window shading (M5) also stands out as the third-best solution providing synergies between mitigation and adaptation targets. It can be addressed by internal or external shading devices, such as awnings, blinds, fins, overhands, shrubs or even external obstacles, for example, trees. This measure reduces discomfort hours up to 131 h in an extremely hot climate, 162 h in a very hot climate, and 280 h in hot climates, along with energy savings of 7.14 kWh/m^2, 6.99 kWh/m^2, and 4.30 kWh/m^2, respectively.

The roof insulation (M1) also showed a good performance creating synergies between adaptation and mitigation. However, other measures such as insulation of windows and reduction of internal gains (heat flow rate of lighting and appliances) showed low synergies. These measures reduce discomfort hours in the range of 21 to 7 h in an extremely hot climate, 25 to 8 h in very hot climates, and 59 to 22 h in a hot climate, along with energy savings of 3.70 kWh/m^2 to 1.14 kWh/m^2 in an extremely hot climate, 2.03 kWh/m^2 to 1.01 kWh/m^2 in a very hot climate, and 1.17 kWh/m^2 to 0.21 kWh/m^2 in a hot climate.

The best energy saving measure for the air-conditioned building was raising the summer set point temperature (SST). Setting the SST to 1℃ higher than the baseline scenario during the day and 1.5℃ higher by night results in an energy saving of 19.74 kWh/m^2 in Sukkur, 19.12 kWh/m^2 in Lahore, and 12.33 kWh/m^2 in Quetta. Similar adaptation steps are being practised in different parts of the world. For instance, in 2005, residents of Japan's central government ministry buildings were advised to set their summer air conditioning temperature to 28℃ until the beginning of September.

Likewise, it is found that not all passive measures are beneficial for the energy and comfort matrix at the same time in all climatic zones. For instance, on the one hand, the insulation of the building envelope reduces thermal cooling demand in all investigated climatic zones (14.43 kWh/m^2 in Sukkur, 8.44 kWh/m^2 in Lahore and 0.78 kWh/m^2 in Quetta) for the air-conditioned scenario. In contrast, insulation increases discomfort hours when building operating in free-running conditions (256 in Sukkur, 365 in Lahore, and 762 in Quetta). Similarly, the performance of other passive measures such as increasing the airtightness of the building envelope or the reduction of thermal breaks was shown beneficial for air-conditioned buildings. However, these options increase thermal discomfort for free-running buildings, showing negative values in Fig. 12.

The results demonstrate that passive measures such as night ventilation, reflective and ventilated roofs, shading of windows, and roof insulation should be prioritised in future building regulations in order to create synergies between mitigation and adaption targets in the built environment. Moreover, changing thermostat settings for air-conditioned buildings has been proved to have a significant potential to mitigate cooling energy demand.

4. Limitation of the study and future directions

This study has some limitations. First, a reference residential building archetype was considered in order to represent a significant portion of the residential building stock in the region. This archetype was numerically evaluated with the same building characteristics in all investigated locations. Thus, only qualitative conclusions can be drawn based on these findings for other building typologies or configurations. Second, only the A2 scenario of IPPC was considered to investigate the building performance under climate change. This represents a specific pathway, which results may differ from other scenarios, such as A1, B1 and B2. Third, retrofitting target values were defined considering the best available technologies according to the Pakistan building code [75], literature review, and other technical handbooks, reports and standards [76–78]. Alternative retrofitting target values may differ from reported findings.

The findings highlight the important role of passive measures in mitigating cooling demand and discomfort hours. However, it is recognised how low-energy and active cooling technologies are also required to promote citizens' wellbeing and health. In this context, other active cooling alternatives such as solar cooling systems or geothermal cooling technologies could present high interest due to the high solar radiation and ground availability in this area [81–83]. However, further research or government subsidies may be required to make them economically viable. Future work will focus on the role of advanced passive and low-energy cooling solutions with synergies to reduce cooling load and indoor discomfort hours in extremely hot climates.

5. Conclusions

This research investigates the best resilient cooling pathway that should be promoted in the built environment of extremely hot countries to maximise synergies between mitigation and adaptation targets. A parametric analysis of climate change impact in Pakistan by 2020, 2050 and 2080 under the A2 (medium–high) emission scenario was developed, comparing the evolution of climate zones, cooling thermal demand (kWh/m^2) and indoor discomfort hours (DH, hours) in buildings. Moreover, different passive cooling alternatives were assessed and compared in order to identify synergies and trade-offs between energy efficiency (energy consumption) and heat resiliency (passive survivability). Based on the results, the following conclusions can be drawn:

Pakistan can be divided into four climate zones according to ASHRAE standard 169: extremely hot dry (0B), very hot dry (1B), hot dry (2B) and warm dry (3B). The results show how a large portion of the country is expected to become much hotter, with the area characterised by an extremely hot dry climate increasing from 36.9% to 78.1% by 2080 under the A2 climate change projections. Under this scenario, cooling energy demand (for air-conditioned buildings) will increase between 20.56 and 66.96 kWh/m^2, and the heat discomfort hours (for buildings without air conditioning, in free-running conditions) in the range of 423 to 1267 hours by 2080.

The passive cooling measures based on night ventilation, reflective and ventilated roofs, shading of windows, and roof insulation were highlighted as those alternatives with more considerable synergies between energy savings and indoor comfort hours in free-running conditions. These passive cooling measures can provide energy savings ranging from 13.1 to 7.1 kWh/m^2 while reducing discomfort hours in the range of 320 to 131 for extremely hot regions. Additionally, raising the set point temperature by 1–1.5℃ for air-conditioned buildings was demonstrated to mitigate cooling energy consumption considerably, up to 19.74 kWh/m^2.

Trade-offs were found with some passive measures between energy savings and passive survivability. The increase of insulation of exterior walls and airtightness of the building envelope was a beneficial passive measure for air-conditioned buildings to reduce thermal cooling demand. However, they increased the indoor discomfort hours in free-running buildings if heat dissipation is not adequately addressed. For extremely hot climates, despite achieving energy savings of 14.4 kWh/m^2, these measures increase discomfort by 256 h, increasing building overheating by 5.1%.

Additional considerations in building design and building codes of extremely hot regions should be considered to encourage appropriate natural ventilation, reflective and ventilated roofs, shading of windows, well-insulated roofs and thermostat settings to enhance the heat resilience of buildings to climate change, even considering the specificities of different local climatic conditions. They provide considerable synergies between energy savings when air conditioning is available and indoor comfort hours during passive survivability.

CRediT authorship contribution statement

Sajid Mehmood: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization, Project administration, Funding acquisition. **Jesus Lizana:** Validation, Formal analysis, Investigation, Writing – review & editing, Visualization, Supervision, Funding acquisition. **Miguel Núñez-Peiró:** Formal analysis, Visualization. **Serguey A. Maximov:** Validation, Writing – review & editing, Funding acquisition. **Daniel Friedrich:** Conceptualization, Methodology, Investigation, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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Appendix

Tables A1, A2 and A3 summary the results of different resilient cooling alternatives in different climates with regards to energy savings (kWh/m^2) and reduction of discomfort hours (DH, hours).

Table A1
Effect of retrofitting techniques on energy savings (kWh/m^2) and reduction of discomfort hours for 2020, 2050 and 2080 in a extremely hot climate.

Extremely hot climate (Sukkur)						
	2020		2050		2080	
Code	Energy savings (kWh/m^2)	Reduction of DH (hours)	Energy savings (kWh/m^2)	Reduction of DH (hours)	Energy savings (kWh/m^2)	Reduction of DH (hours)
M1	10.77	82	11.22	102	12.99	101
M2	14.43	−256	16.60	−303	21.11	−283
M3	3.70	7	4.12	14	5.69	41
M4	0.02	−12	0.12	−11	0.17	−16
M5	7.14	131	7.26	127	8.00	177
M6	2.53	44	2.37	47	2.91	64
M7	5.31	81	5.35	85	6.18	124
M8	11.98	171	11.90	199	12.67	231
M9	8.36	35	8.35	35	9.16	51
M10	1.14	14	0.88	18	1.29	20
M11	1.83	21	1.61	24	2.06	30
M12	9.31	−12	11.55	−10	16.25	−12
M13	13.13	320	16.68	296	25.15	316
M14	19.74	0	20.38	0	22.09	0

Table A2
Effect of retrofitting techniques on energy savings (kWh/m^2) and reduction of discomfort hours for 2020, 2050 and 2080 in a very hot climate.

Very hot climate (Lahore)						
	2020		2050		2080	
Code	Energy savings (kWh/m^2)	Reduction of DH (hours)	Energy savings (kWh/m^2)	Reduction of DH (hours)	Energy savings (kWh/m^2)	Reduction of DH (hours)
M1	7.57	88	8.24	116	9.46	108
M2	8.44	−365	10.81	−396	14.91	−398
M3	2.03	8	2.75	35	4.03	32
M4	0.11	−13	0.19	−19	0.41	−26
M5	6.99	162	7.33	190	7.91	195
M6	2.41	50	3.00	78	2.91	76
M7	5.02	88	5.30	120	5.78	132
M8	10.89	198	11.00	264	11.33	268
M9	7.96	41	8.20	61	8.64	64
M10	1.01	18	1.07	30	1.21	27
M11	1.69	25	1.77	43	1.95	39
M12	7.23	−15	9.87	−20	14.57	−22
M13	9.02	297	12.22	311	21.00	312
M14	19.12	0	19.97	0	21.16	0

Table A3
Effect of retrofitting techniques on energy savings (kWh/m^2) and reduction of discomfort hours for 2020, 2050 and 2080 in a hot climate.

Hot climate (Quetta)						
	2020		2050		2080	
Code	Energy savings (kWh/m^2)	Reduction of DH (hours)	Energy savings (kWh/m^2)	Reduction of DH (hours)	Energy savings (kWh/m^2)	Reduction of DH (hours)
M1	4.37	273	5.07	253	6.09	168
M2	0.77	−762	2.62	−627	5.29	−459
M3	0.24	12	0.40	16	0.70	20
M4	0.04	−8	0.04	−10	0.08	−10
M5	4.30	280	4.66	246	5.09	216
M6	1.54	101	1.70	85	1.78	77
M7	3.11	172	3.39	150	3.71	133
M8	8.57	557	9.10	510	9.71	416
M9	5.53	70	5.93	64	6.37	55
M10	0.73	42	0.81	33	0.82	29
M11	1.17	59	1.28	46	1.34	42
M12	0.34	−22	0.50	−18	0.84	−15
M13	10.12	564	9.47	502	9.02	446
M14	12.33	0	13.36	0	14.61	0

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