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Climate-change-induced overheating prevention capacity of Montenegrin residential buildings

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ABSTRACT

The study assesses the overheating prevention capacity of residential buildings in Montenegrin municipalities by considering key factors, such as building characteristics, occupant behaviour, and current and future climate conditions. Firstly, a survey was conducted to explore occupants' perception of thermal comfort and to identify passive design measures that exist or should be implemented for overheating prevention in residential buildings. Secondly, climate data were analysed to determine current and future projected climate conditions, while the bioclimatic potential for overheating prevention was evaluated for each municipality. Lastly, this study applied a developed methodology for assessing the overheating prevention capacity of residential buildings by correlating the survey results to climate data. The climate analysis shows an increase in the overheating periods, with the highest vulnerability to global warming in the colder locations. Accordingly, policymakers and building designers must take proactive steps to improve resilience to climate change in these areas. In addition, the research revealed that many passive design measures are underutilised by the occupants, who primarily rely on air conditioning to prevent overheating. Therefore, more complex passive measures must be implemented in Montenegrin buildings to ensure resilience and avoid excessive overheating under the predicted future climate conditions.

1. Introduction

Vulnerability to global warming and climate change hazards such as droughts, floods, wildfires, and heat waves is a growing problem in the built environment. In the wake of global warming and urbanisation, the overheating of buildings is expected to worsen while climate adaptation is called into question. However, global warming has localised impacts, and its effects may differ from country to country. Montenegro faces increasing vulnerability to climate hazards, with projections indicating increasing severity and frequency. Key indicators include rising air and sea temperatures, rising sea levels, and changes in extreme weather events [1]. The results of climate projections (RCP8.5 emission scenario) indicate that the mean annual temperature across the country will rise by up to 2 °C, 3 °C and 5.5 °C by 2040, 2070 and 2100, respectively [2]. This rise in temperature highlights, among other things, the importance of addressing thermal comfort, energy efficiency, climate adaptation and resilience, as well as other sustainability aspects in buildings [3]. Even though climate data indicates Montenegro's high vulnerability to climate change, there is a lack of knowledge and information about the Montenegrin residential building stock climate adaptability and resilience. Therefore, the present study addresses this critical knowledge gap by evaluating the capacity of residential buildings' climate adaptability to the projected global warming until the end of the century.

1.1. The context of montenegro

Montenegro is located in the EUCRA Southern Europe land and marine region [4] at the junction of the Dinaric Alps and the central Mediterranean (Fig. 1). The country's total area is 13,812 km^2, and the marine water area is about 2,540 km^2. Montenegro is divided into 25 municipalities (Fig. 3), with Podgorica as the capital. According to the 2023 census [5], Montenegro has 633,158 inhabitants. Over the last 20 years, the total population has grown modestly from 603,152 in 2000, with an average annual growth rate of 0.15 %. The urbanisation rate in Montenegro grew relatively fast – from 58.5 % in 2000 to 67.5 % in 2020 [6] – with the municipality of Podgorica housing 28.5 % of the entire population [5]. It is projected that the population of Montenegro will decline to around 540,000 inhabitants by 2050 [7,8], while urbanisation

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will increase [7]. According to the data from 2011 [9], detached houses represent the highest share of the building stock, housing 61 % of dwellings, while 3 or more apartment buildings represent 39 % of dwellings. Around 50 % of buildings in Montenegro are between 20 and 50 years old, less than 30 % are older than 50, and below 20 % are less than 20 years old [9]. Montenegro is a small economy driven by the service sector, particularly tourism, agriculture and manufacturing [2], with a 2023 GDP per capita of € 6,900 [10] and a Human Development Index of 0.844 [11].

Montenegro has a Mediterranean climate with warm and somewhat dry summers and mild and relatively humid winters. The average annual air temperature ranges from 5.6 °C in Plav, 958 m above sea level, to 17.1 °C in Bar at the coast (Fig. 1 and Table B1 in Appendix B). The average annual precipitation varies from 800 mm in the far north to around 5,000 mm in the far southwest of the country [2]. The complexity of the weather and climate dynamics arises from its geographical position, the dissected nature of its terrain, the mountains and valleys, their orientation, the movement and interaction of the air masses, large water bodies such as the Adriatic Sea and Lake Skadar, and the proximity to a large land surface in the north (Fig. 1). Climatic variations occur depending on the distance from the sea and elevation, resulting in several distinct climate types within the region. These range from warm temperate Mediterranean at the coast and around Podgorica to cooler humid continental climates in northern and northeastern regions with higher elevations and occasional intermediate temperate climate (for more information, see Table B1 in Appendix B). Montenegro is highly vulnerable to climate change. Impacts have already been felt and are expected to worsen [2]. In the last seven decades (1950–2020), the average yearly temperature in Montenegro has increased by 0.203 °C per decade, while warming intensity has more than doubled to 0.542 °C per decade since 1991 [14]. The observed warming trend is higher than the average for the EUCRA Southern Europe region, which experienced 0.197 °C of warming per decade between 1950 and 2020 and 0.419 °C per decade between 1991 and 2020. The comparison of global warming trends with the broader region of Southern Europe underscores the relevance and significance of addressing its impacts in the context of Montenegro. Therefore, adaptation actions and strategies are necessary and urgent as Montenegro is above average exposed to the effects of global warming.

1.2. Literature review

Climate-change-induced overheating can lead to decreased occupant productivity, health problems, and strain on the power grid due to increased cooling demand [15–17]. While global warming is projected to induce more and more overheating in buildings, air conditioning is expected to become the predominant heat reduction strategy globally, even though it is costly compared to passive overheating prevention measures, has a higher environmental impact, is less accessible to vulnerable populations and is prone to power outages [18]. According to the IEA Net Zero Scenario projections, global space cooling energy demand will increase from 26.66 EJ in 2022 to 32.34 EJ in 2030 [19], which will put considerable pressure on energy grids and the economy. Therefore, incorporating overheating prevention measures into existing building stock to increase their passive overheating resilience will reduce the energy demand for cooling and increase the inherent resilience of the built environment. However, in order to do so, an overheating assessment is necessary, while several approaches exist to evaluate the overheating risk.

For example, Bo et al. [20] used validated simulation results and empirical data to assess the overheating risk of residential buildings in severe cold and cold regions of China using the hours of exceedance (HE) method. From May to September, overheating was recorded for 0.4–37.6 % of total time in the south-facing bedrooms. Similar conclusions in the same context were also drawn by Yu et al. [21]. In contrast, Guo et al. [22] analysed the overheating risk of urban villas in the subtropical region of China using Indoor Overheating Degree (IOD) and Indoor Overheating Hour (IOH) methods to assess future overheating risk. The authors concluded that in future scenarios, commonly used low-cost retrofit measures (i.e., glazing, shading) will have a reduced impact on overheating duration but will decrease the degree of overheating. Furthermore, Tian et al. [23] evaluated the overheating risk of a typical Norwegian detached house under present and future climate conditions using the Passive House Planning Package (PHPP) and CIBSE TM 59 overheating evaluation criteria guidelines while highlighting that the PHPP method is not ideal for assessing overheating risk when considering occupancy patterns. It was highlighted that large windows and increased airtightness can increase overheating risk, particularly in future climate scenarios. Another study was conducted by Silvero et al. [24] in historic residential buildings in Asunción, Paraguay, with a humid subtropical climate. Two thermal comfort assessment methods were employed to asses overheating rate: the statistical approach and the adaptive thermal comfort approach. The results demonstrated that climate change will intensify thermal discomfort, exposing an urgent need for building codes to address the challenges posed by climate change.

While residential buildings are expected to face high overheating risk, especially in future climates, passive solutions are effective but not necessarily efficient for preventing overheating in future [25]. For residential buildings in temperate climates, using solar shading devices with natural ventilation is a crucial passive approach to ensure summer comfort [26,27] and reduce cooling energy demand. Therefore, efficient shading and cooling by natural ventilation are common passive strategies to reduce overheating and are projected to become even more critical in future climates. In this context, Simson et al. [28] analysed the summer thermal comfort in apartment buildings in Estonia and showed

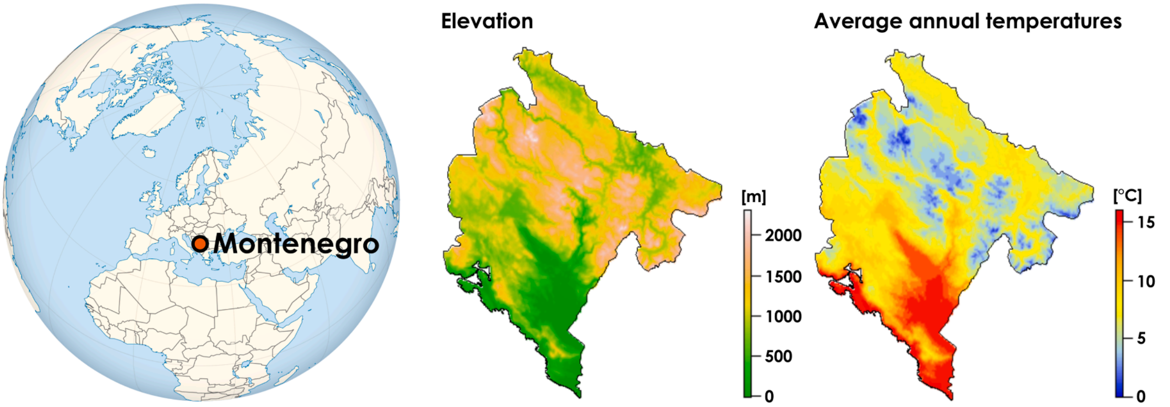

Fig. 1. Location (left), elevation (middle) and average annual temperature (right) of Montenegro (the maps sourced from [12], globe sourced from [13]).

that 68 % of them do not comply with the summer thermal comfort requirements. The main reasons for that are large windows without shading and insufficient area of operable windows.

Furthermore, survey data for 59 suites across two buildings in Toronto, Canada, indicated the thermal discomfort of the occupants in the cooling season 53 % of the time [29]. The authors concluded that solar control on the east- and west-facing glazed surfaces and improved airtightness should be addressed to improve thermal comfort. Dartevelle et al. [27,30] investigated the overheating risk in 23 nZEB houses in the temperate climate of Belgium. The cases with a higher risk of overheating had larger unshaded glazing surfaces and were more often west-oriented. The authors emphasised the importance of occupant behaviour in reducing the risk of overheating through shading and other environmental controls. Similar conclusions were drawn by Singh et al. [31] for 20 residential buildings in Belgium.

In the same way, Colclough and Salaris [32] studied overheating in 50 Irish nZEBs by monitoring their indoor temperatures. They found that 26 % of these new buildings experienced overheating, and 48 % exceeded the WHO recommended temperature for at least 10 % of the year. Issues like improper heat pumps and inadequate controls, such as limited external shading or window restrictors, hindered occupants' ability to manage overheating. A study by Ozarisoy [33] analysed the risk of overheating in a terraced house in London, UK, during the prolonged heat waves. The findings showed that passive design strategies, such as shading and natural ventilation, were highly effective in reducing energy use and creating a comfortable indoor environment for occupants.

Moreover, a re-analysis conducted by Lomas and Drury [34] on a set of 750 temperature measurements in the UK living rooms and bedrooms during a hot summer in 2018 showed that energy efficiency measures geared towards reducing the energy use for heating do not exacerbate summertime overheating. However, they provided evidence that internally applied thermal insulation increases indoor summertime temperatures. Similar to the previously mentioned studies, they also expose the importance of shading and ventilation as crucial passive overheating prevention strategies, indicating that apartments were more susceptible to overheating than houses among the studied buildings. In addition, highly insulated buildings can overheat in temperate climates, even in winter, while design-level solutions such as cross-ventilation, solar control and occupant behavioural changes can act as preventive measures [35]. Lastly, Thapa [36] studied the risk of overheating in low-rise, naturally ventilated residential buildings of northeast India (cold, hot and humid climates) and found that the buildings were insufficient in mitigating the impacts of global warming. At the same time, indoor comfort was better in buildings with higher ventilation rates and U-values.

Be that as it may, Attia et al. [37], based on a study of 26 European countries, highlighted that existing overheating calculation methods are predominantly outdated, failing to fit climate-proof buildings. Therefore, overheating assessment should prioritise comfort-based, multi-zonal, and time-integrated methodologies to address these shortcomings. Moreover, homeowners play a crucial role in enhancing resilience by deciding whether to implement preventive measures in their homes. Murtagh et al. [38] surveyed English homeowners to understand their willingness to protect their homes against overheating. They concluded that psychological factors were more influential than socioeconomic factors. Past overheating experiences influenced their perception of the threat, but not directly their motivation to take action. The knowledge about protective measures positively influenced their belief in their ability to cope. However, in Montenegro, homeowners have limited knowledge about potential passive climate adaptation measures beyond thermal insulation, particularly when it comes to summer overheating [39].

1.3. Knowledge gap and study objective

Considering the above-described context and the specifics of Montenegro, the authors conducted several studies analysing the impacts of climate change, building overheating risk and occupants' knowledge about overheating prevention measures (see refs. [39–41]). These studies concluded that bioclimatic (i.e., passive) strategies have great potential for overheating prevention under current and future projected climates but are underutilised. However, there is no comprehensive knowledge about the overall adaptability to climate change and climate resilience at the level of Montenegrin building stock. Based on this insight, the authors concluded that it is necessary to comprehensively analyse the capacity of the Montenegrin residential building stock to withstand climate-change-induced overheating up to the end of the 21st century. As such, the following objectives were defined:

- To form an inventory of the Montenegrin residential buildings, including their existing status of overheating prevention measures and the acceptability of implementing additional measures based on occupant self-reports.
- To identify which passive building measures are needed in residential buildings for overheating mitigation due to the projected climate change.
- To propose a building overheating mitigation strategy for each climate cluster based on the overheating prevention capacity assessment.

The presented study has direct implications for policymakers, who can use the results to guide the timely adoption of legislative frameworks directing the Montenegrin residential building stock towards climate resilience through various climate change adaptation strategies, building retrofit actions, and promotion. The presented overheating prevention capacity assessment approach is also valuable for policymakers, designers and engineers to successfully implement climate adaptation actions.

2. Methods

To achieve the objectives of the study, a three-segment methodological approach was used. First, an occupant survey was prepared and conducted, and its results were analysed. Then, climate data for current and future projected conditions were obtained and interpreted. In the last step, ability of the Montenegrin residential buildings to prevent overheating was assessed by comparing the survey results and climate data analysis. The details of the methodology are given in Fig. 2 and the following subsections.

2.1. Questionnaire and surveying

The survey was conducted to collect data, gather respondents' opinions, and gain insight into the currently used and potentially acceptable additional measures to prevent overheating in residential buildings in Montenegro. In addition, the survey also explored the occupants' perception of summer thermal comfort and acceptance. In order to collect statistically inferable data, a descriptive-type study with multiple-choice questions and predefined answers was prepared. The survey was implemented in Google Forms and distributed nationwide throughout all 25 municipalities of Montenegro (Fig. 3) using the mailing lists of the Chamber of Engineers of Montenegro and the University of Montenegro. The surveying was conducted from October 15th to November 12th, 2023, with 1034 completed questionnaires collected, of which 1029 were valid and used in further analysis. This represents *a* ± 3.04 % margin of error at a 95 % confidence level, which was determined based on the Montenegrin Census for 2023, where a total of 217,441 households were reported for Montenegro [5]. Because the number of respondents from 11 municipalities (see Fig. 3) was lower

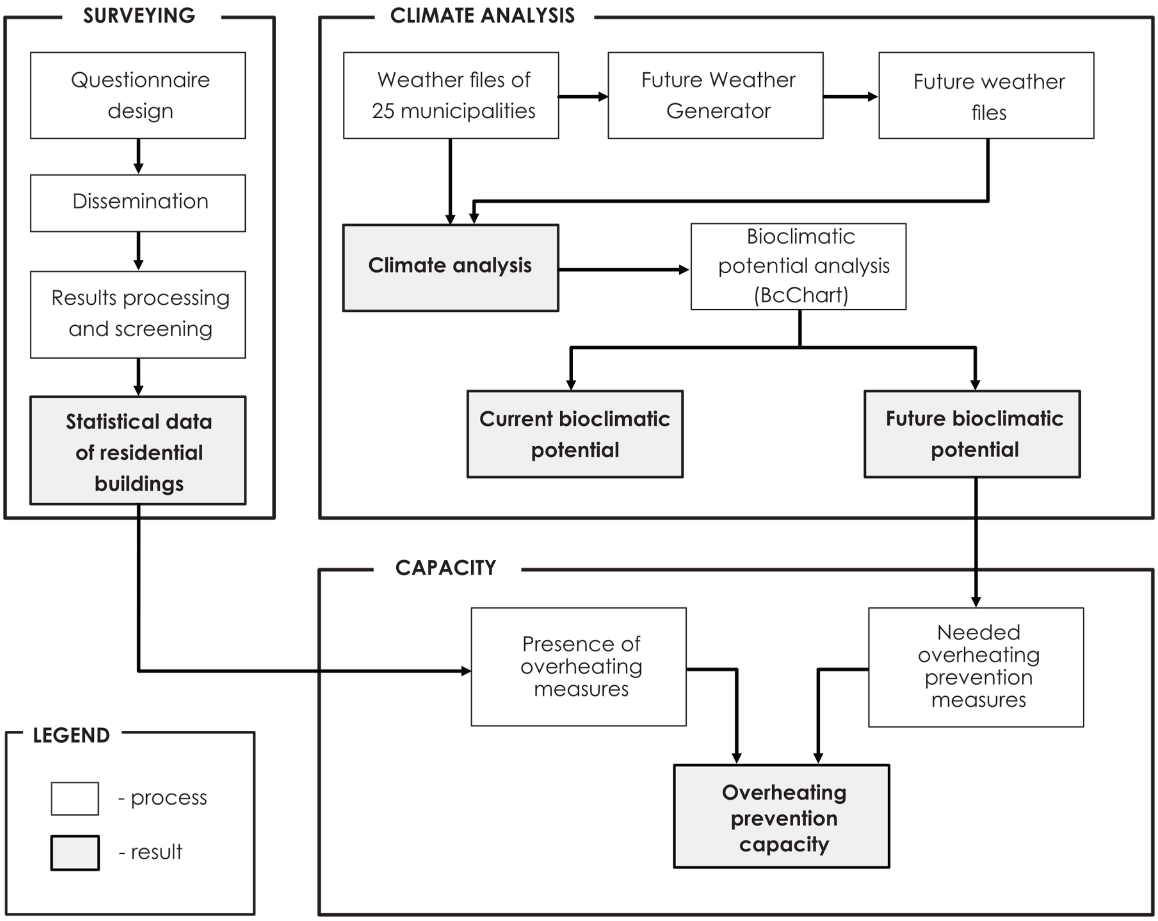

Fig. 2. Flowchart of study methodology structure.

than 1 % of the total survey's responses, these were not considered representative and were excluded from further analysis. The remaining 14 municipalities were included in the interpretation of the results and the subsequent overheating prevention capacity assessment. These 14 municipalities represent 87 % of Montenegro's total population and comprise 969 out of 1029 valid survey responses. The survey questionnaire is presented in Appendix A, while municipality-specific demographic and climatological information is presented in Appendix B. The survey consisted of four thematic sections with a total of 18 questions. The thematic sections were the following:

- **Socio-demographic section** (3 questions): the age of the surveyed occupants, the municipality where they reside, and the average monthly income in the household.
- **Building characteristics section** (8 questions): building typology, age and construction material, dwelling floor level and orientation, façade colour, window type and information about previous energy-related retrofitting actions. In the survey interpretation, all the residential buildings constructed of concrete, brick or stone were determined to have high thermal mass. Similarly, all the cases with a reported light-coloured façade were determined to have light external surfaces.
- **Summer thermal comfort and thermal acceptance section** according to ISO 28,802 [42] (4 questions): 7-point sensation scale according to ISO 7730 [43] for daytime and nighttime thermal comfort perception and acceptance of daytime and nighttime thermal comfort. The 7-point scale was used to determine thermal sensation vote (TSV), a measure used to assess subjective perception of thermal comfort.
- **Overheating prevention measures section** (3 questions): identification of measures in place in the buildings, measures to be added, and measures applied before turning on the air conditioning.

About 47 % of respondents were between 20 and 39 years old, 30 % were between 40 and 59 years old, and approximately 15 % were in the under 19 age group. Less than 5 % of respondents were in the age group of 60 years and older. About 40 % of the respondents reported that the average monthly income of their household was between € 1,000 and € 2,000, with an additional 30 % falling into the € 500 to € 1,000 group. These data show that most respondents belonged to middle-class and lower-income households, as the average net income per capita in February 2023 in Montenegro was € 771 [44]. The remaining respondents belonged to other income categories or refused to disclose their monthly income. The most represented building typologies were single- and double-family homes, accounting for 48 %, while multi-apartment buildings accounted for about 42 %. The remaining respondents lived in other buildings, such as terraced houses, urban villas, and multi-apartment residential towers. 40 % of respondents lived in buildings between 20 and 50 years old, while a comparable share of almost 38 % lived in buildings between 5 and 20 years old. Approximately 40 % of the buildings were either entirely or partially energy retrofitted.

2.2. *Climate analysis*

For each municipality (Fig. 3), a climate file was sourced from the European Commission's Photovoltaic Geographical Information System PVGIS-SARAH2 database [45], containing climate data between 2005 and 2020. Climate data in the form of EPW files were downloaded for

Fig. 3. Map of Montenegro with marked municipal division, municipality administrative centres and coordinates of sourced climate files (the map was adapted from [32] and modified by changing colours, removing hydrology and adding labels and scale).

the administrative centre of the municipality. The exact coordinates of climate files are presented in Fig. 3. These files were considered as reference climate data representing the current state of the climate in each municipality. Furthermore, the files were the basis for creating future projected climate files according to the IPPC's SSP5–8.5 climate change scenario [46] for the 2066–2095 time frame using the Future Weather Generator v2.0 software [47,48]. The SSP5–8.5 climate change scenario describes a world with high greenhouse gas emissions, competitive and globalised markets, high technological development and resource and energy-intensive lifestyles [49]. In other words, the scenario describes a world in which the projected increase of mean surface temperature compared to the pre-industrial baseline will increase by more than 4 °C by the end of the century [46].

The implemented climate analysis of current and future projected climate data consisted of two parts. The first part was a basic climate analysis focusing primarily on climatological parameters affecting or describing the influence of climate on buildings. Therefore, average annual temperatures (T_L), average monthly temperatures, Heating Degree-Days with a heating base temperature ($T_{b,H}$) of 10 °C (HDD_{10}, see Eq. (1)), and Cooling Degree-Days with a cooling base temperature ($T_{b,C}$) of 18 °C (CDD_{18}, see Eq. (2)) were calculated from the climate files. HDD and CDD are established top-down methods for rough estimations of the average heating and cooling needs of buildings based on the average external daily temperatures (T_{ex}) at a specific location.

Furthermore, they can be used to illustrate the impacts of climate change on the average energy use of the building stock [50–52].

$$\mathrm{HDD} = \sum_{i=1}^{365} \left(T_{b,H} - T_{ex,i}\right)^{+} \text{ if } \mathrm{T_{b,H}} - \mathrm{T_{ex,i}} > 0 \tag{1}$$

$$\mathrm{CDD} = \sum_{i=1}^{365} \left(T_{b,C} - T_{ex,i}\right)^{+} \text{ if } \mathrm{T_{ex,i}} - \mathrm{T_{b,C}} > 0 \tag{2}$$

The second part of the climate analysis consisted of a bioclimatic potential analysis executed using the BcChart v2.3 tool [53] based on an upgraded Olgyays's bioclimatic charts theory [54]. Bioclimatic potential, calculated using BcChart, assesses climate suitability for passive building design. The method uses climate data (temperature, relative humidity, solar radiation) to determine when outdoor conditions align with human indoor thermal comfort, presuming typical clothing and moderate activity. Indoor thermal comfort is appropriate when the air temperature is roughly between 21 and 27 °C (lower if the relative humidity is higher) and the relative humidity is between 20 and 80 %. The specific climate conditions determine whether passive building design (e.g., shading, natural ventilation) can contribute to achieving thermal comfort or, on the other hand, if active systems (heating, cooling) are required. Through such bioclimatic potential analysis, we can identify suitable passive building design measures to optimise building thermal performance and reduce reliance on mechanical heating or cooling. Overall, the bioclimatic potential analysis yields two opposite design strategy groups. Firstly, heat dissipation and heat exclusion strategies (for definitions, see ref. [55]) are suitable for warmer climates/periods. Under these two, passive design measures, such as shading, ventilation, and high thermal mass, as well as passive measures for hot and arid conditions (denominated as Sh, Ve, Htm, and Ha), are recommended. When none of the former applies, active measures such as mechanical cooling and dehumidification are needed (denominated as Mc). Secondly, the heat retention and heat admission strategies (for definitions, see ref. [55]) are suitable for colder climates/periods. Under these two, passive design measures, such as passive solar heating and heat retention (e.g., thermal insulation), are recommended (denominated as Psh and Hr). When solar radiation is inadequate or temperatures are extremely low, conventional heating is needed to maintain thermal comfort (denominated as Ch). Detailed methodology for the assessment of bioclimatic potential is available in references [56,55] and [57]. In the present study, the bioclimatic potential was evaluated only for overheating prevention (i.e., Sh, Ve, Htm, Ha and Mc; see also Fig. 4) for each municipality for the current and future climate and presented as a percentage of the year in which a specific passive measure is needed to maintain thermal comfort.

Based on the climatological and bioclimatic analysis, the climate files were clustered for the current and future projected climate. The defined climate clusters represent municipalities with similar climate characteristics and, consequently, similar bioclimatic building design adaptation measures that translate into indoor thermal comfort and building energy use. The main purpose of clustering was to simplify the interpretation of the results and their application in the real world.

2.3. *Overheating prevention capacity assessment*

In the final step, the overheating prevention capacity of the Montenegrin residential building stock was analysed. For this purpose, a novel approach was proposed. Firstly, for each of the municipalities with a relevant number (i.e. > 10) of survey responses (see Fig. 3), the necessary overheating prevention actions were derived from the bioclimatic potential analysis for the current and future climates, namely if there is a need for shading, ventilation, high thermal mass or passive measures for hot and arid conditions at a particular location. If the percentage of the year when a specific overheating prevention action is needed to maintain thermal comfort was higher than or equal to 1 % (i.e. ≥ 88 h), the action was marked with a "1" and otherwise with a "0". Secondly, if an overheating prevention action was marked with a "1", the occupant self-reports were used to determine whether passive overheating prevention measures corresponded to the required action in the

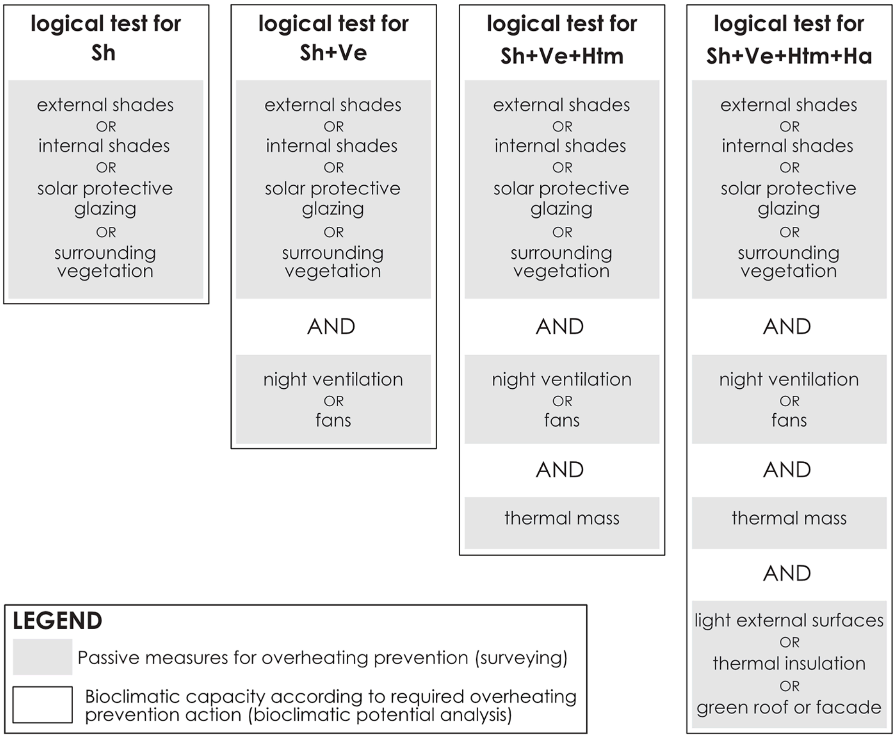

Fig. 4. Logical tests used to determine the overheating prevention capacity by linking passive measures for overheating prevention (determined by a survey) and results of bioclimatic potential analysis.

building/household of the survey respondents. If the required passive measure was present, the building/household was marked to have the capacity of overheating prevention with a specific measure, i.e. it was marked with "1". For example, if the climate in a specific municipality demands shading (Sh) as an overheating prevention action and in a particular building any of the passive measures providing shading, such as external shades, internal shades, solar protective glazing or surrounding vegetation (see Fig. 4), were reported as present, the overheating prevention capacity with shading for that building was defined as "1". The overheating prevention capacity was marked as "0" if the required measures were absent. However, as we move towards the more complex overheating prevention actions (Fig. 4, from left to right), such as Ve+Sh (ventilation and shading), Htm+Ve+Sh (high thermal mass and ventilation and shading) and Ha+Htm+Ve+Sh (passive measures for hot and arid conditions and high thermal mass and ventilation and shading), these actions require redundancy by also including the previous actions (e.g. logical test for Ve+Sh requires: (night ventilation OR fans) AND shading) to achieve the overheating prevention capacity. Lastly, the share of residential buildings in a specific municipality with a given overheating prevention capacity was calculated. The analysed overheating prevention capacities were defined for shading, ventilation, high thermal mass and passive measures for hot and arid conditions (Fig. 4).

3. Results

3.1. Survey analysis

Survey data on the share of buildings/households with specific overheating prevention measures arranged in ascending order of T_L for each municipality are presented in Table 1. According to the responses, the results show that buildings in Montenegro are mainly (i.e. > 92.9 %) constructed of high thermal mass materials (i.e., concrete, brick, or stone), regardless of the municipality. Furthermore, buildings have predominantly light colour façades, with the lowest share of 38.9 % in Berane and the highest share of 90.5 % in Ulcinj. A relatively small share of respondents reported that their buildings are thermally insulated, with the lowest share of 14.3 % in Plav and the highest share of 40.0 % in Rožaje. The data in Table 1 also show that thermal insulation in Montenegrin buildings is not correlated with T_L.

Under 40 % of dwellings in Plav, Rožaje and Pljevlja were reported to have external shading. In municipalities with T_L above 8 °C, the reported share of external shading was more than 50 %, except for Ulcinj (T_L = 16.67 °C), where 42.9 % of dwellings were reported to have external shading. This is significantly less than in the case of Bar, which has a comparable T_L but almost 27 percentage points more buildings with external shading devices. Nevertheless, the data on the external shading in buildings correlate with the T_L of the locations, as warmer locations also have higher shares of external shading installed. On the other hand, there is a slightly less noticeable trend in the use of internal shading, namely a higher use in municipalities with T_L below 12 °C (i.e., between 28.0 % in Pljevlja and 44.4 % in Berane) and a decrease to below 20 % at T_L above 12 °C, with Tivat and Herceg Novi being the exceptions (see Table 1). On the other hand, shading with surrounding vegetation is not that common, as the share of buildings with such shading ranges between 33.3 % in Tivat and 5.6 % in Berane, while solar protective glazing is almost non-existent in the surveyed building stock, with the highest share of 9.1 % reported for Budva.

The highest utilisation of night ventilation was reported for Budva at 51.5 %, which is one of the warmest municipalities (T_L = 14.90 °C). In comparison, the lowest use of night ventilation was recorded in Ulcinj (14.3 %), the second warmest municipality in Montenegro. Overall, night ventilation is not commonly used as an overheating prevention measure. At the same time, its use does not seem to be in line with the T_L of the municipalities (Table 1). Like solar protective glazing, fans are also surprisingly rare, with the highest share of use at 7.0 % in Bar. On the same note, the implementation of green roofs or façades is limited in all municipalities (Table 1). Lastly, the use of air conditioning (AC) shows a noticeable trend in terms of the T_L, as all municipalities with the T_L below 12 °C are characterised by shares between 42.1 % (Nikšić) and

Table 1
Share of buildings/households with specific overheating prevention measures, arranged according to T_L.

Municipality	T_L [°C]	Night ventilation [%]	Thermal insulation [%]	High thermal mass [%]	Light facade colour [%]	External shading [%]	Internal shading [%]	Solar protective glazing [%]	Surrounding vegetation [%]	Green roof or façade [%]	Fans [%]	Air conditioning [%]
Plav	5.62	21.4	14.3	92.9	78.6	28.6	35.7	0.0	21.4	0.0	0.0	7.1
Rožaje	6.08	36.7	40.0	100.0	66.7	33.3	36.7	3.3	20.0	0.0	3.3	3.3
Pljevlja	7.21	33.6	29.9	96.3	58.9	37.4	28.0	0.0	15.9	2.8	2.8	12.1
Berane	7.28	38.9	16.7	100.0	38.9	50.0	44.4	0.0	5.6	11.1	5.6	27.8
Bijelo Polje	8.76	24.1	20.7	100.0	72.4	58.6	41.4	6.9	13.8	0.0	0.0	24.1
Nikšić	10.13	34.2	19.3	95.6	77.2	61.4	28.1	2.6	25.4	5.3	2.6	42.1
Kotor	12.63	27.7	19.1	97.9	72.3	63.8	19.1	2.1	27.7	4.3	0.0	68.1
Tivat	12.76	47.6	38.1	100.0	95.2	81.0	33.3	4.8	33.3	9.5	4.8	76.2
Tuzi	13.75	17.6	23.5	100.0	76.5	70.6	17.6	0.0	11.8	0.0	5.9	76.5
Herceg Novi	13.84	41.1	17.8	97.3	63.0	64.4	26.0	8.2	23.3	5.5	4.1	74.0
Podgorica	14.17	38.3	31.8	99.0	74.1	71.4	18.7	4.0	27.9	4.0	3.0	77.4
Budva	14.90	51.5	15.2	93.9	69.7	69.7	18.2	9.1	12.1	3.0	6.1	78.8
Ulcinj	16.67	14.3	28.6	100.0	90.5	42.9	14.3	0.0	19.0	9.5	4.8	71.4
Bar	17.12	44.2	27.9	97.7	88.4	69.8	18.6	2.3	27.9	2.3	7.0	65.1

3.3 % (Rožaje). On the other hand, warmer municipalities (T_L > 12 °C) have consistently higher shares of dwellings with installed ACs, with 65.1 % in Bar and 78.8 % in Budva.

Table 2 shows the results of the question we asked the occupants about which overheating prevention measures they think should be further implemented in their buildings. A significant proportion of respondents (between 23.5 and 42.9 %) in municipalities with T_L > 8 °C would implement solar protective glazing as a protection against overheating. Surprisingly, in colder locations (T_L < 10 °C), more respondents would opt for the installation of AC than for the use of other passive measures (Table 2). For example, 39.9 % of respondents in Rožaje would like to install AC in their homes. However, only 30.8 % would apply thermal insulation, and only 6.5 % would apply night ventilation. Less than a quarter of the respondents living in colder municipalities (T_L < 10 °C) believe that night ventilation should be used in their dwellings as an overheating prevention measure. Interestingly, respondents in warmer municipalities were more prone to selecting both night ventilation and thermal insulation as measures that should be included in their buildings, although both measures are more effective in colder climates. On the other hand, responses from municipalities with colder climates showed a higher preference for external shading with a higher overall share than in warmer locations, as the latter already have external shading that is predominantly used in their dwellings (Table 1).

Table 3 shows the passive design measures that respondents use to prevent overheating before opting for AC. According to the results, the most frequently used measure before turning on the AC is external shading, with relatively evenly high shares across Montenegro, with only the municipalities of Plav, Pljevlja, and Ulcinj below 40 %. Concurrently, respondents from all municipalities reported that they often used night ventilation before resorting to AC. However, the frequency of its use is less uniform than in the case of external shading (Table 3), with the highest shares of over 60 %reported in Budva, Berane, Tivat, and Bar. Respondents also reported using daytime ventilation and internal shading as measures before resorting to AC, while only a very low share (i.e. < 14 %) reported using fans.

Finally, the occupants were also asked to report their perception of thermal comfort during the day and night. More than half of the surveyed occupants (58 %) rated summer thermal comfort as hot, warm and slightly warm in the daytime, and 44.4 % at nighttime. To illustrate the results, the mean daytime TSV and mean nighttime TSV were calculated and presented for each municipality, in parallel with the share of AC systems present in the households (Fig. 5). A clear positive correlation between T_L and mean daytime and nighttime TSV can be observed, which also translates into the percentage of homes with installed ACs. The respondents from colder locations (T_L < 12 °C) reported slight thermal discomfort (mean daytime TSV = 0.5–0.8). Since the reported mean thermal sensation in these municipalities is near neutral, the implementation of passive measures for overheating prevention would be appropriate. On the other hand, respondents from warmer locations (T_L > 12 °C) reported a substantially higher level of thermal discomfort (mean daytime TSV = 0.9–1.2). Even though AC is widely used in these locations, passive design measures should be used to improve thermal comfort and reduce the need for mechanical cooling. Furthermore, improper sizing or inadequate operational efficiency of air conditioning systems might also be the source of detected inadequate thermal comfort, while intermittent use of air conditioning to save on electricity bills or due to personal preferences may also lead to elevated TSV.

3.2. Climate analysis

Based on current climate data, the T_L of the analysed municipalities ranges between 5.6 °C (Plav) and 17.1 °C (Bar) and is proportional to the elevation of the location and its proximity to the Adriatic coast (Fig. 6).

Table 2
Share of survey respondents, who think that specific measures should be incorporated into their buildings/households, arranged according to T_L.

Municipality	T_L [°C]	Night ventilation [%]	Thermal insulation [%]	External shading [%]	Internal shading [%]	Solar protective glazing [%]	Surrounding vegetation [%]	Green roof or façade [%]	Fans [%]	Air conditioning [%]
Plav	5.62	7.1	21.4	21.4	21.4	14.3	7.1	0.0	7.1	35.7
Rožaje	6.08	6.7	30.0	30.0	6.7	16.7	13.3	13.3	3.3	23.3
Pljevlja	7.21	6.5	30.8	30.8	3.7	19.6	13.1	3.7	6.5	39.3
Berane	7.28	16.7	22.2	27.8	11.1	22.2	27.8	22.2	16.7	33.3
Bijelo Polje	8.76	20.7	20.7	13.8	0.0	24.1	13.8	10.3	3.4	34.5
Nikšić	10.13	8.8	34.2	17.5	6.1	29.8	15.8	15.8	8.8	26.3
Kotor	12.63	17.0	34.0	8.5	6.4	29.8	27.7	19.1	10.6	8.5
Tivat	12.76	9.5	52.4	19.0	4.8	42.9	19.0	19.0	9.5	28.6
Tuzi	13.75	17.6	29.4	17.6	5.9	23.5	11.8	11.8	5.9	23.5
Herceg Novi	13.84	11.0	28.8	17.8	6.8	31.5	20.5	19.2	9.6	19.2
Podgorica	14.17	12.2	31.6	15.2	4.5	37.8	37.8	34.8	11.2	11.7
Budva	14.90	3.0	42.4	9.1	18.2	33.3	33.3	21.2	9.1	9.1
Ulcinj	16.67	14.3	19.0	14.3	9.5	33.3	14.3	9.5	4.8	28.6
Bar	17.12	16.3	41.9	16.3	4.7	39.5	27.9	23.3	9.3	11.6

Table 3
Share of the survey respondents who use specific passive design measures to prevent overheating before they opt for air conditioning, arranged according to T_L.

Municipality	T_L [°C]	Daytime ventilation [%]	Night ventilation [%]	External shading [%]	Internal shading [%]	Fans [%]
Plav	5.62	21.4	28.6	7.1	50.0	7.1
Rožaje	6.08	16.7	36.7	40.0	30.0	10.0
Pljevlja	7.21	25.2	42.1	26.2	40.2	3.7
Berane	7.28	38.9	66.7	55.6	38.9	0.0
Bijelo Polje	8.76	13.8	31.0	48.3	20.7	3.4
Nikšić	10.13	33.3	49.1	54.4	36.0	3.5
Kotor	12.63	38.3	53.2	55.3	31.9	6.4
Tivat	12.76	33.3	61.9	47.6	38.1	9.5
Tuzi	13.75	17.6	47.1	64.7	17.6	11.8
Herceg Novi	13.84	37.0	47.9	57.5	21.9	13.7
Podgorica	14.17	30.8	59.0	69.4	27.6	7.7
Budva	14.90	51.5	72.7	54.5	48.5	3.0
Ulcinj	16.67	28.6	28.6	33.3	19.0	0.0
Bar	17.12	46.5	60.5	60.5	27.9	2.3

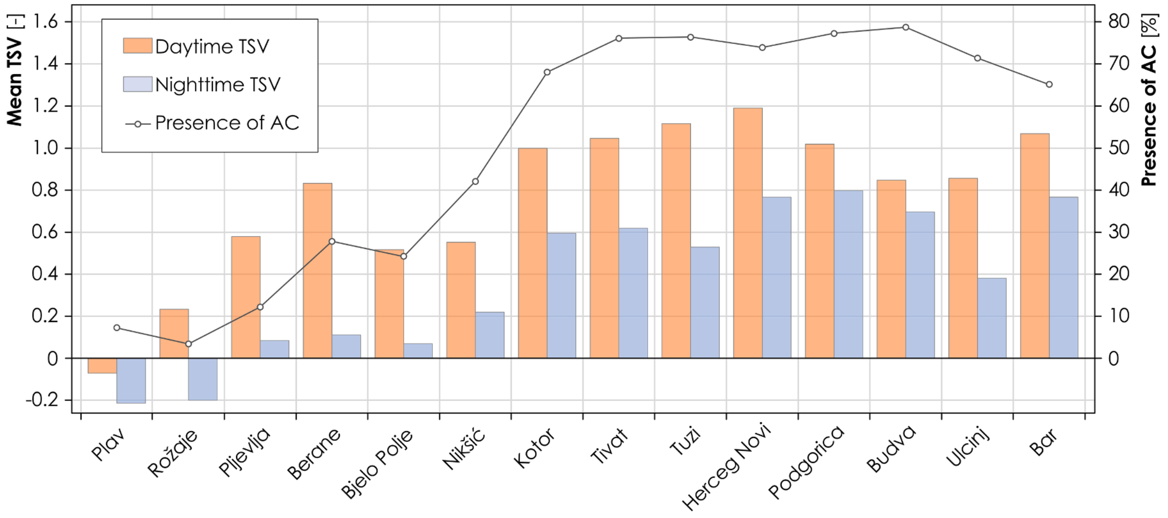

Fig. 5. Daytime and nighttime thermal sensation vote (TSV) and the percentage of buildings with installed air conditioning.

The data presented in Fig. 6 also show that more than 60 % of the Montenegrin population is concentrated at low elevations (i.e. < 100 m) with higher average yearly temperatures ($T_L > 12.5$ °C). A more detailed analysis of the current climate, including average monthly temperatures, Köppen Geiger and ASHRAE climate types, is presented in Appendix B, Table B1. Based on future projected climate data according to the SSP5–8.5 scenario, the T_L of the analysed locations will increase on average by 4.7 °C by the end of the century. Therefore, the T_L is projected to be between 10.3 °C in Plav and 21.6 °C in Bar (Fig. 6 and Table B2 in Appendix B), with the seasonal increase in projected warming being the highest in summer and lowest in spring.

The analysis of yearly average temperatures and population distribution shows that under current climate conditions, 64.25 % of the population lives at locations with $T_L > 12.5$ °C and 13.23 % with $T_L > 15$ °C. Additionally, 18.31 % of the population lives at locations with $T_L < 7.5$ °C. However, due to the projected climate change, the Montenegrin population will live at T_L above 10 °C by the end of the 21st century. Moreover, 69.75 % of the population is projected to live at $T_L > 15$ °C and 13.67 % at $T_L > 20$ °C (see Fig. 6 and Appendix B). The substantial increase in annual average temperature will also translate into a shift in the projected CDD_{18} and HDD_{10} values for each municipality (Fig. 7). As CDD and HDD can be used as a simplified proxy for energy use in buildings, these data can indicate the changes in heating and cooling needs. Notably, a substantial increase in cooling demand is projected, as CDD_{18} will increase by an average of 710 Kdays (between 419 in Mojkovac and 1197 Kdays in Herceg Novi) by the end of the century. On the other hand, an average reduction in HDD_{10} of 518 Kdays (between –66 in Bar and –803 Kdays in Plav) is projected. In general, locations with

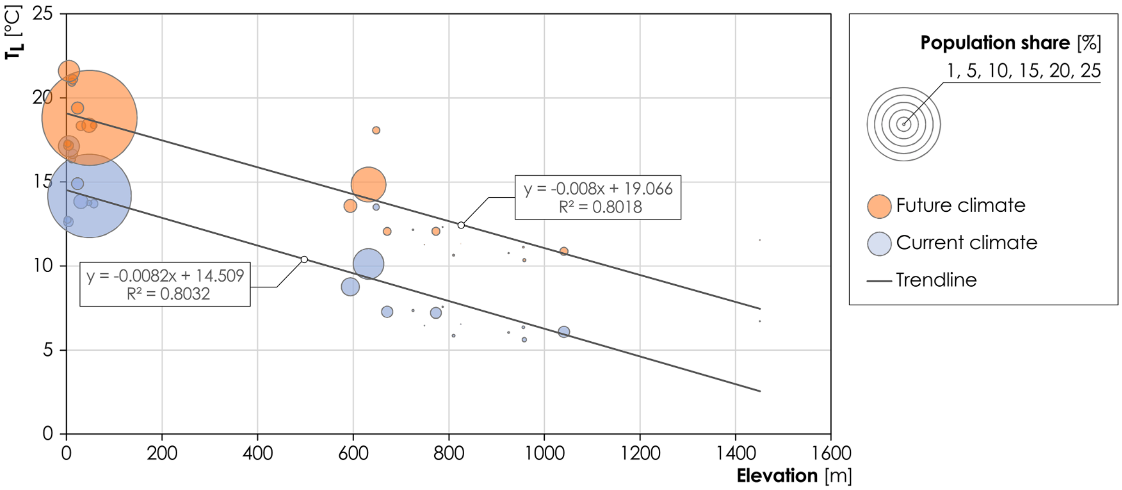

Fig. 6. T_L, elevation and population share of each municipality for the current and future projected climate.

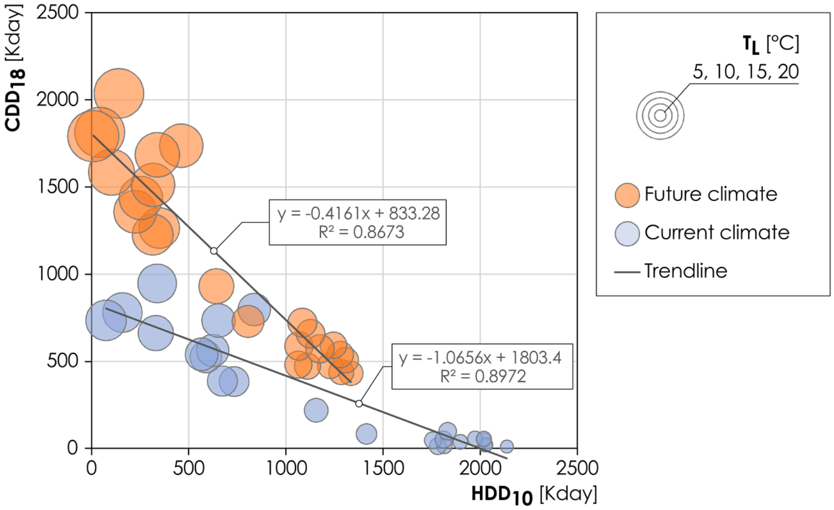

Fig. 7. CDD_{18}, HDD_{10}, and T_L for each municipality under the current and future projected climate.

higher T_L are projected to become almost exclusively cooling-driven as HDD_{10} will decrease below 500 Kdays. On the other hand, locations that currently have a relatively cool climate (i.e., $T_L < 8$ °C) will also see a drastic increase in CDD (Fig. 7), as all these locations will have a CDD_{18} above 250 Kdays by the end of the century.

Based on the current and future projected climate data analysis, municipalities can be clustered into three groups with specific climatic characteristics (Table 4). These climate clusters can be clearly seen in Fig. 7, with two groups (Cluster 1 and Cluster 2) at opposite ends of the CCD and HDD spectra and two locations with transitional characteristics (i.e., Cluster 3 – municipalities of Nikšić and Bijelo Polje). Table 4 states climate and bioclimatic attributes of each cluster under the current and projected climate. The devised clusters also correspond to the Montenegrin climate zones 1, 2 and 3 proposed by Novikova et al. [9], with only the municipalities of Cetinje and Bijelo Polje being classified differently.

Besides climate analysis, a bioclimatic potential analysis was performed to identify the necessary passive building design actions for each location. Under the current climate, the municipalities of Ulcinj, Bar, and Zeta (Fig. 8) experience the longest periods requiring overheating prevention. Additionally, 11 locations (44 %) require overheating prevention measures for more than 15 % (i.e., 55 days) of the year. On the other hand, 12 locations (48 %) need overheating prevention actions less than 3 % (i.e., 11 days) of the year. However, the overheating period is projected to increase by an average of 60 days by the end of the 21st century due to global warming. The highest increase is projected in Kotor (+76 days), followed by Bijelo Polje (+73 days), Tivat (+72 days), Ulcinj (+70 days) and Nikšić (+70 days). In Ulcinj and Bar, the overheating period is projected to extend over 50 % of the year. On the other hand, the overheating period is projected to increase the least in Kolašin, from 5 to 48 days (+43 days). Concerning the climate clusters as defined in Table 4, according to the bioclimatic analysis, the average current overheating period lasts 1.3 %, 24.6 % and 4.8 % in Clusters 1, 2 and 3, respectively. In the 2066–2095 time frame, the overheating period is projected to be 16.4 %, 42.0 % and 24.4 % in Clusters 1, 2 and 3, respectively. The most significant increase of 19.4 percentage points on average compared to the current climate is projected in Cluster 3. Although the overheating period is projected to increase in all municipalities, the increase is most concerning where currently little or no overheating prevention measures are needed, namely in the colder locations of Cluster 1. The results in Fig. 8 show that due to global warming, in Cluster 1 the most needed overheating prevention measures in the future would be shading (Sh), followed by the use of high thermal mass with ventilation (Htm+Ve+Sh). It could be argued that the same is valid in the transitional locations of Nikšić and Bijelo Polje in Cluster 3. On the other hand, in the warmer locations of Cluster 2, it will be

Table 4

Climate clusters defined according to climate analysis.

CLIMATE CLUSTER		Current climate (2005–2020 climate data)	Future projected climate (2066–2095 time frame, SSP5–8.5 scenario)	Municipalities
Cluster 1 (cold)	**Climate characteristics**	$HDD_{10} > 1500$ Kday $CDD_{18} < 250$ Kday $T_L < 8\ ^\circ C$	$HDD_{10} > 1000$ Kday $CDD_{18} < 1000$ Kday $T_L < 13\ ^\circ C$	Andrijevica Berane Gucinje Kolašin Mojkovac Petnjica Plav Pljevlja Plužine Rožaje Šavnik Žabljak
	Bioclimatic characteristics	• Dominated by heating needs, with negligible or no need for overheating prevention. • The building design should focus on heat retention and heat admission (see ref. [55]) bioclimatic strategies. • Indoor thermal comfort can be achieved using passive solar heating alone for approx. 10 to 15 % of the year.	• Dominated by heating needs, however, some overheating measures are recommended. • The building design should focus on heat retention and heat admission (see ref. [55]) bioclimatic strategies with shading during summer. • Efficient shading is needed to prevent overheating in buildings for up to 23 % of the year.	
Cluster 2 (warm)	**Climate characteristics**	$HDD_{10} < 1000$ Kday $CDD_{18} > 250$ Kday $T_L > 12\ ^\circ C$	$HDD_{10} < 500$ Kday $CDD_{18} > 1000$ Kday $T_L > 15\ ^\circ C$	Bar Budva Cetinje Danilovgrad Herceg Novi Kotor Podgorica Tivat Tuzi Ulcinj Zeta
	Bioclimatic characteristics	• Overheating prevention measures are necessary between 15 and 31 % of the year. • The building design should incorporate several passive overheating prevention measures (e.g., shading, ventilation and high thermal mass) and passive solar heating in winter. • The need for conventional heating is below 35 % of the year.	• Overheating prevention measures are necessary up to 50 % of the year. • The building design should focus on multiple measures, from heat dissipation and heat exclusion (see ref. [55]) bioclimatic strategies with simultaneous provision for passive solar heating in winter. • The need for conventional heating is below 26 % of the year.	
Cluster 3 (transitional)	**Climate characteristics**	$1500\ \text{Kday} > HDD_{10} > 1000$ Kday $CDD_{18} < 250$ Kday $12\ ^\circ C > T_L > 8\ ^\circ C$	$1000\ \text{Kday} > HDD_{10} > 500$ Kday $CDD_{18} < 1000$ Kday $15\ ^\circ C > T_L > 13\ ^\circ C$	Bijelo Polje Nikšić
	Bioclimatic characteristics	• Dominated by heating needs, with a need for overheating prevention with shading up to 7 % of the year. • The building design should focus on heat retention and heat admission (see ref. [55]) bioclimatic strategies. • Indoor comfortable conditions can be achieved up to 22 % of the year with passive solar heating and efficient shading.	• Dominated by heating needs. However, overheating measures such as shading, ventilation, and high thermal mass are necessary for up to 26 % of the year. • The building design should focus on heat retention and heat admission (see ref. [55]) bioclimatic strategies with simultaneous inclusion of passive overheating prevention measures.	

necessary to apply passive measures for hot and arid conditions (Ha+Htm+Ve+Sh) in combination with shading (Sh), ventilation (Ve+Sh) and high thermal mass (Htm+Ve+Sh) to prevent overheating, which is not the case under the current climate. What is more, the future climate in Ulcinj and Bar is projected to be so muggy that during most of August and part of July, indoor thermal comfort will be unattainable without mechanical cooling and/or dehumidification (Mc+Sh in Fig. 8).

3.3. *Overheating prevention capacity assessment*

Following the survey and climate analysis, an overheating prevention capacity assessment was conducted to propose an overheating mitigation strategy (Fig. 9). The assessment is based on relating occupant self-reports on overheating prevention measures available in their households/buildings with the passive design measures needed for overheating prevention according to the SSP5–8.5 climate change scenario for 2066–2095. The results of the capacity analysis show the fitness of the Montenegrin households to adapt to climate change through passive design measures. The analysis also identifies future actions that would increase the resilience of the building stock to future projected climate.

The results indicate that the building stock analysed in the survey has a high overheating prevention capacity connected to the availability of solar protection (i.e., Sh). Namely, on average 79 % of buildings are equipped with some form of solar protection (Fig. 9). This also applies for the municipalities of Plav, Rožaje, and Pljevlja (Cluster 1), where there is no need for overheating protection with shading under current climate conditions (see Fig. 8). Interestingly, the lowest capacity of 51 % was identified in Ulcinj, the second warmest location under current and future projected climate (see Section 3.1 and Appendix B). However, Ulcinj also has one of the highest shares of installed air conditioners (Fig. 9). Unfortunately, the trend of high overheating prevention capacity does not continue with other passive overheating prevention measures such as shading with ventilation (i.e., Ve+Sh), high thermal mass with nighttime ventilation and daytime shading (i.e., Htm+Ve+Sh) and passive measures for hot arid conditions (i.e., Ha+Htm+Ve+Sh). In the case of Ve+Sh, only 19 % (from 51 % in Budva to 9 % in Ulcinj) of the buildings utilise these measures in municipalities where the measures are applicable (Fig. 9). Similar applies to Htm+Ve+Sh, with 29 % of buildings (from 51 % in Budva to 9 % in Ulcinj) and Ha+Htm+Ve+Sh, with 17 % of buildings (from 42 % in Budva to 9 % in Ulcinj) that have the capacity to utilise such passive measures (Fig. 9).

Lastly, let us suppose that the overheating capacity of the municipalities in Cluster 1 (i.e., Plav, Rožaje and Pljevlja), which will need overheating prevention measures under the projected climate, is compared to those in Clusters 2 and 3, which already need them under the current climate. In such case, it becomes apparent that the differences are unexpectedly slight. In particular, for the case of Sh, the Cluster 1 municipalities have only 8 percentage points lower average overheating capacity than the remaining locations. A similar situation with a slightly higher difference of 11 percentage points is also evident for Htm+Ve+Sh. However, the share of buildings with installed air conditioners (Figs. 5 and 9) between these two groups is substantially different. This indicates that the potential for reducing overheating in Montenegrin residential buildings using passive means is underutilised, irrespective of the current climate conditions.

4. Discussion

The study investigated the capacity of Montenegrin residential buildings to resist overheating caused by rising temperatures up to the

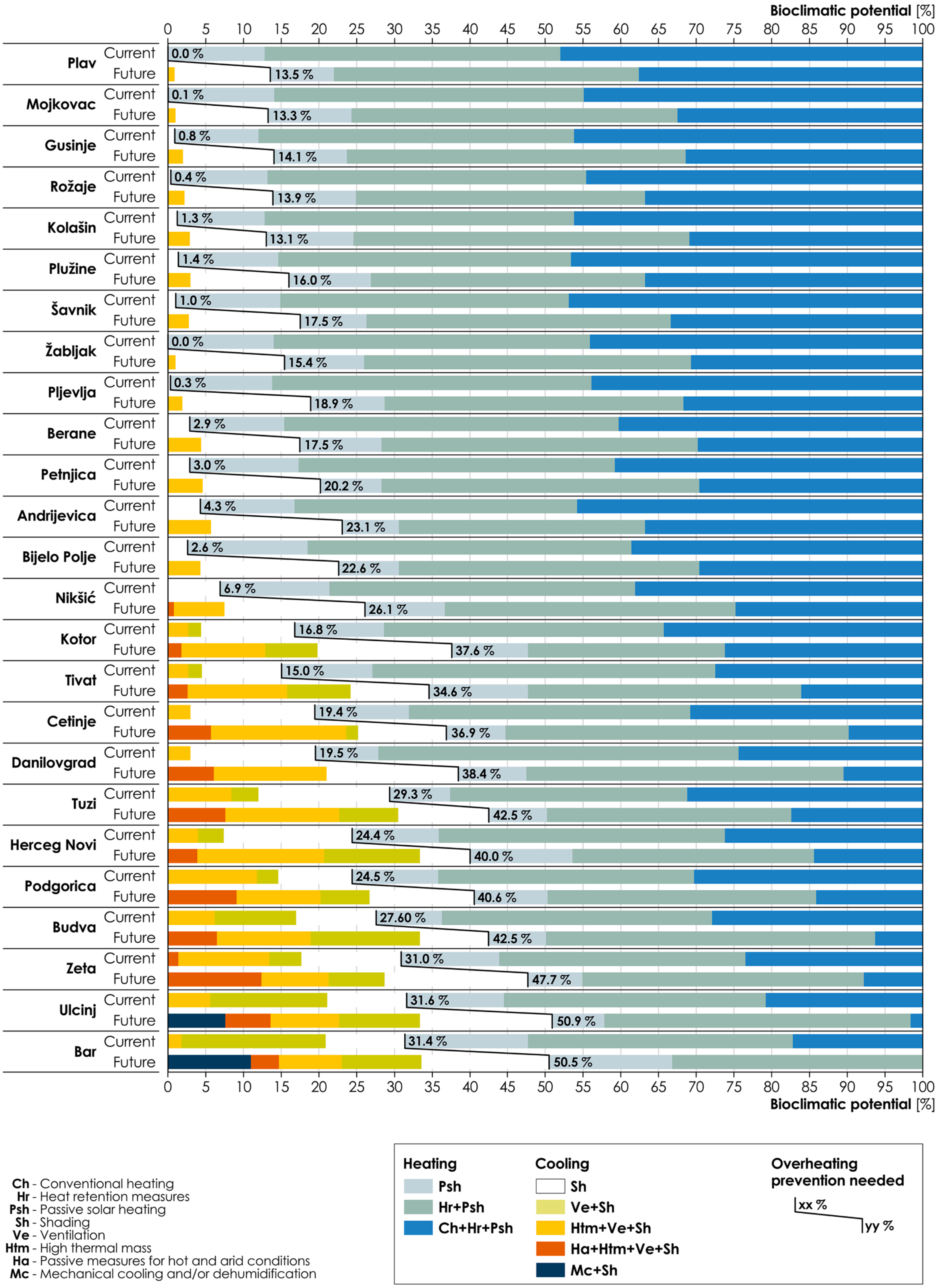

Fig. 8. Current and future projected bioclimatic potential of each municipality.

end of the century. A broad based survey among the occupants of Montenegrin buildings was performed to draw up an inventory of the existing overheating prevention measures incorporated in residential buildings. The survey showed that the most represented overheating prevention measures are high thermal mass and light façade colours. However, both are a consequence of the prevailing building practices in Montenegro, where most residential buildings are built of stone, concrete or brick and plastered with light-coloured render. On the other hand, the use of night ventilation as an overheating prevention measure was shown to be underutilised. This was expected, since comparable findings were demonstrated by Pajek et al. [39] for a thermally uninsulated residential building in Montenegro and by Dartevelle et al. [27]

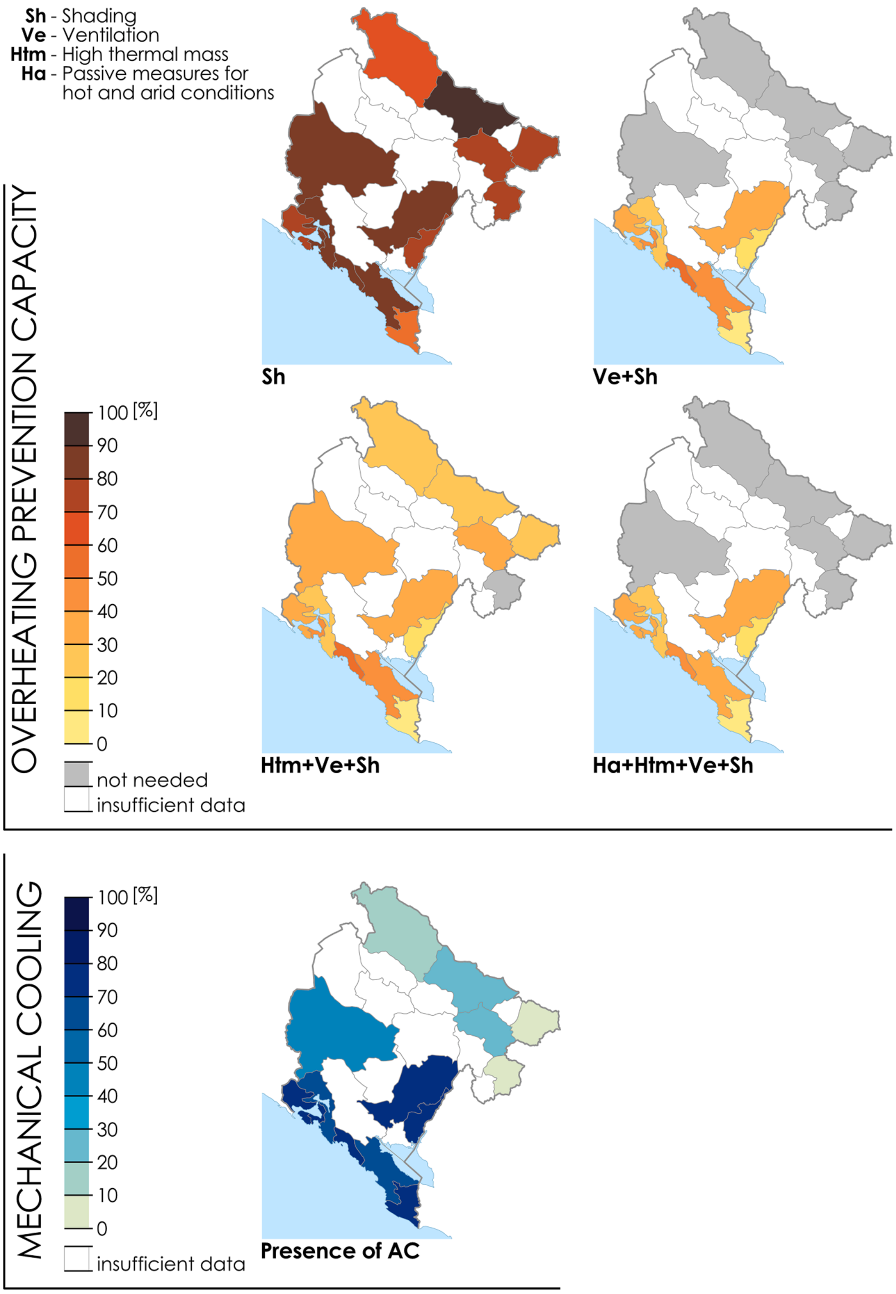

Fig. 9. Overheating prevention capacity (top) and share of air conditioning present in residential buildings (bottom) for the relevant municipalities in Montenegro (the maps were adapted from [32] and modified by changing colours and removing the hydrology).

for an insulated building in Belgium. Consequently, this also reduces the efficiency of using high thermal mass as an overheating control measure, since the stored heat cannot be effectively dissipated by nighttime ventilation. Other commonly present overheating prevention measures are external shading and other shading measures, such as internal shading and surrounding vegetation. Surprisingly, the thermal insulation of building envelopes is also underrepresented. However, it can be potentially explained by the high financial burden of applying thermal insulation on existing buildings for Montenegrin households despite its long-term economic and environmental benefits [58]. Low thermal insulation adoption rates are particularly surprising for the colder locations of Cluster 1. Survey results about household income showed that respondents living in municipalities of Cluster 1 have below-average monthly income, where 47 % of respondents receive less than € 1,000, a substantially higher share than for the entire sample (38 %). This corresponds to the above-average at-risk-of-poverty rate in this region, with 37.6 % of the population being at risk, which is 17.3 percentage points higher than the national average [59]. Air conditioning is primarily installed in warm locations of Cluster 2, but is also present in Clusters 1 and 3. When asked which additional measures they would be willing to install in their homes, residents mostly opted for the installation of thermal insulation, solar protective glazing and, particularly in climate Cluster 1, air conditioning and external shading.

The bioclimatic potential analysis was executed to complement the survey results and identify the need for passive design measures in the context of the current and future projected climate. The analysis showed clear distinctions in the required passive design measures for climate adaptation among the three Montenegrin climate clusters under the current and future climate. Most worrying, however, is the impact of global warming on the colder locations of Cluster 1. Under the SSP5–8.5 climate change scenario, locations in Cluster 1 will see an increased need for passive overheating prevention measures, which are almost non-existent under the current climate and in the existing building stock. This suggests that proactive measures to strengthen the climate resilience of buildings in these locations are needed at the level of policy and building design approaches. Otherwise, global warming will intensify the overheating strain already present in Clusters 2 and 3. Some locations of Cluster 2 are projected to become almost exclusively cooling-driven. In contrast, the need for overheating prevention in Cluster 3 (i. e., Bijelo Polje and Nikšić) is projected to be comparable to the current situation in Cluster 2.

The subsequent overheating prevention capacity assessment revealed that beyond solar protection, Montenegrin buildings/households lack the adequate application of more complex passive measures to prevent overheating under future projected climate. This applies to the municipalities that already experience the need for overheating protection under the current climate and to those that will experience it under the future climate (e.g. Plav, Rožaje and Pljevlja). Interestingly, there is no significant difference in the overheating prevention capacity between the two groups of municipalities, indicating that the current climate conditions do not affect the overall willingness of Montenegrin households to combat overheating. These alarming conclusions indicate that the Montenegrin building stock is ill-equipped in terms of the passive overheating prevention measures needed to provide appropriate climate change resilience without relying almost exclusively on mechanical cooling.

Overall, the study showed that the occupants find the conditions during the warmer part of the year uncomfortable and are aware of the overheating risk. Nevertheless, many passive measures identified as needed/effective by the bioclimatic analysis, such as night ventilation and external shading, remain underutilised by occupants whose primary approach to building overheating prevention is air conditioning. These findings are essential, as passive design measures perform significantly better than active ones in reducing energy burdens and increasing sustainability in urban-scale households [60], while providing passive resilience and survivability during extreme events such as heat waves and power outages [17,61]. Taylor et al. [62] have already warned that the increasing risk of overheating requires immediate implementation of adequate, future-ready, robust regulatory standards and guidelines in Northern and Central European housing, emphasising the significant role of occupants. It is evident that Southeastern European countries, such as Montenegro, are also at increased overheating risk; therefore, timely climate adaptation policies and regulations are vital.

4.1. Implications for policy and practice

One of the challenges facing society in the current century is the future climate-proofing of the building stock and increasing its climate resilience [61,63]. Climate readiness of buildings is critical for maintaining indoor thermal comfort and, at the same time, avoiding overloading the energy grid in hot months and during heat waves. From the bioclimatic analysis and the analysis of the overheating prevention capacity of Montenegrin warm locations (i.e., Clusters 2 and 3), we can learn what to expect in colder locations (i.e., Cluster 1) in about 50 years and how great the need for passive measures to prevent overheating at these locations will be. Furthermore, it was reported that thermal comfort in residential buildings in climate Cluster 2, is already inadequate, particularly during daytime, even though a relatively high share of air conditioning is installed in dwellings (see Fig. 5). This calls for more comprehensive climate adaptation strategies and policies that should include the following implications:

- First and foremost, policymakers should promote and enact legislation and guidelines that require new buildings and retrofits (e.g., energy efficiency retrofits) to integrate passive building design measures to prevent overheating under future climate conditions. In particular, efficient shading devices should be stipulated throughout Montenegro. At the same time, additional passive measures like night ventilation cooling in conjunction with high thermal mass should be implemented to ensure redundancy and a more significant reduction in indoor temperatures [64,65]. How this requirement should be enacted in future policy is beyond the scope of the present study. Nevertheless, a combination of requirements through energy efficiency codes, promotions through systems of subsidies, and designers' education would probably be the most effective approach in the long term. Moreover, besides adding thermal insulation and installing air conditioning, shading was among the most acceptable measures for the surveyed occupants to incorporate into their buildings. This indicates the population's willingness to future climate-proof buildings.
- In climate Clusters 2 and 3, current building practices of constructing buildings with high thermal mass and light-coloured façades should be supplemented by night ventilation cooling. For ventilation cooling to become a viable overheating prevention strategy, buildings should be designed with clever arrangements of spaces and openings that allow cross-ventilation and/or stack ventilation. In this regard, the architectural layouts of floorplans are of central importance and particularly crucial in multiapartment buildings, as single-side-oriented apartments are underperforming in ventilation cooling efficiency [66,67]. At the same time, wind speed, urban configuration and density should be accounted for when designing adequate ventilation cooling approaches [68]. In contrast, issues of urban noise [69], safety, and the potential positive or negative cross-effects of shading on ventilation effectiveness [70,71] must be addressed during the design process. Meanwhile, fans and automated systems for window openings could also be promoted to increase the effectiveness of natural ventilation cooling [72]. The exposed complexity indicates that including efficient ventilation cooling into current Montenegrin building practices is not going to be an easy task, particularly not in the case of building retrofits, as interventions in such buildings are limited by existing context (e.g. floorplan layout, location, orientation, etc.). Survey results show that occupants know this measure and want to use it before using air conditioners. Unfortunately, the ventilation cooling strategy remains underutilised. Therefore, more effort should be put into educating occupants on effectively utilising ventilation cooling to its fullest. On the other hand, building designers should be provided with knowledge through professional associations and formal education on designing buildings that efficiently incorporate ventilation cooling into the overall building design concept.
- Measures such as thermal insulation of building envelopes, application of cool roofs, and increasing the albedo of external surfaces and/or green façades and roofs should be promoted in Cluster 2. When multiple measures are combined and coordinated, a more significant impact of passive overheating prevention approaches can be expected [64,73]. This is particularly true for warmer locations (i.e., Cluster 2), but is also beneficial for more temperate ones (i.e., Clusters 3 and 1).
- Since the overheating prevention capacities of municipalities in climate Clusters 2 and 3 have been determined as inadequate, and while more than 80 % (projected to increase to over 85 % in the future) of the population lives in them, the primary focus of policymakers should be on promoting, stimulating and demanding the overheating prevention capacities in these municipalities to limit the increase in the use of air conditioning and strengthen the climate resilience of buildings and consequentially of the population.

Even though the above-described actions are essential, passive measures, particularly during extreme weather events, do not guarantee that indoor conditions are safe, especially for vulnerable populations [61]. Therefore, active measures such as air conditioning are essential for appropriate indoor thermal comfort. As discussed above, they are widely present in Montenegrin buildings, and their use is expected to increase due to climate change. However, air conditioning should not be the only way to maintain indoor comfort during warmer parts of the year, as this is an unacceptable vulnerability during power outages and extreme events.

4.2. Study limitations

This study has potential limitations. Firstly, the reliability of the data gathered by self-reports is questioned, as we are not entirely sure how well users could assess whether specific overheating prevention measures are present or how effective they are. For example, when occupants reported the presence of interior shading (e.g., curtains), it is not clear if it was installed in the entire household or only in specific rooms, etc. At the same time, evaluating the effectiveness of the reported measures for overheating prevention is impossible. Consequentially, the evaluated overheating prevention capacity may overestimate the actual capacity of the Montenegrin building stock. Another limitation in the context of the climate study comes from the selected high-emissions climate change scenario, i.e., SSP5–8.5. The selected scenario represents a very high baseline emission scenario, but is the most meaningful for climate resilience analysis, as it represents an extreme situation (i.e., worst-case scenario). Lastly, in the case of bioclimatic analysis, the limitation of the study lies in the chosen method, in which neither climatic extremes nor the effect of urban overheating are included in the bioclimatic analysis. Therefore, this limitation also affects the overheating capacity assessment, as the need for overheating prevention measures may be underestimated.

5. Conclusion

The paper aimed to assess the climate adaptability of the Montenegrin residential building stock and its resilience in response to the significant temperature increase over the past decades. A new methodology for assessing the overheating prevention capacity of residential buildings for current and future projected climates was proposed. The approach is appropriate for identifying strategic directions for built environment development, such as determining passive measures for overheating prevention. Compared to urban energy modelling the method does not require building modelling and provides generally applicable guidelines. However, the energy-related impacts across the building stock are not directly addressed. The method combines the definition of the presence of overheating prevention measures with an advanced bioclimatic potential analysis. The implementation of passive design measures can ensure the passive resilience of buildings during increased overheating risk. On the other hand, survey respondents expressed their willingness to use passive overheating prevention measures to improve thermal comfort. Nevertheless, measures such as night ventilation are currently underutilised by the occupants who prefer air conditioning.

Moreover, this research highlights the importance and urgency of implementing a comprehensive national climate adaptation strategy for the Montenegrin residential building stock. The discussed implications for policymakers and practitioners underline the importance of applying bioclimatic design measures to prevent future the projected overheating-related risks in residential buildings. Combined with sustainable building practices, these measures can substantially mitigate overheating-related risks and ensure thermally comfortable housing even during extreme events. Notably, the study demonstrated that the Montenegrin residential building stock has a relatively low overheating capacity and is ill-equipped for the climate conditions projected for the end of the century. Therefore, new climate adaptation policies and regulations should stipulate passive design measures in new and retrofitted buildings to promote the long-term climate resilience and sustainability of the built environment. Beyond mere legislative demands, policymakers should also implement campaigns to raise occupant awareness about the benefits of using more complex passive design measures to prevent overheating under future projected climate and reduce reliance on air conditioning.

CRediT authorship contribution statement

Mitja Košir: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Ivana Ćipranić:** Writing – original draft, Methodology, Investigation. **Marija Jevrić:** Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition. **Jaka Potočnik:** Writing – original draft, Validation, Data curation. **Luka Pajek:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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.

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Appendix A

Below is a translated version of the survey questionnaire; the original was in Montenegrin.

Respected,

As part the project of scientific and technological cooperation between the Faculty of Civil Engineering of the University of Montenegro and the Faculty of Civil Engineering and Geodesy of the University of Ljubljana, we are investigating the possibility of implementing specific measures on residential buildings in order to better resist projected climate changes. Your participation is essential for research success, as your answers will give us insight into the condition and use of the building in which you live.

The anonymous survey will take you 5–10 min to complete. The collected data will be considered confidential and analysed as a whole (not on the level of individual responses). They will be used exclusively for this research.

We greatly appreciate your cooperation in this research. Thank you very much!

Demographic data

- *What age group do you belong to?*
  - ○ *under 19 years*
  - ○ *from 20 to 39 years*
  - ○ *from 40 to 59 years*
  - ○ *60 years and more*
- *The amount of monthly household income is:*
  - ○ *below 500 €*
  - ○ *500 – 1,000 €*
  - ○ *1,000 – 2,000 €*

  - *2,000 – 3,000 €*
  - *more than 3,000 €*
  - *I don't want to disclose*
- *In which municipality do you live?*

  ____

Summer thermal comfort perception

- *What is your dominant perception of summer thermal comfort in your apartment/house during daytime?*
  - *cold*
  - *cool*
  - *slightly cool*
  - *neutral*
  - *slightly warm*
  - *warm*
  - *hot*
- *Do you think the temperature during the day in your apartment/house is acceptable/unacceptable?*
  - *acceptable*
  - *unacceptable*
- *What is your dominant perception of summer thermal comfort in your apartment/house during nighttime?*
  - *cold*
  - *cool*
  - *slightly cool*
  - *neutral*
  - *slightly warm*
  - *warm*
  - *hot*
- *Do you think that the temperature during the night in your apartment/house is acceptable/unacceptable?*
  - *acceptable*
  - *unacceptable*

Residential building information

- *The building you live in is:*
  - *single or double-family home*
  - *terraced house*
  - *urban villa (2–4 floors, maximum four apartments per floor)*
  - *multi-apartment building (up to eight floors)*
  - *residential tower (more than eight floors)*
  - *What is the age of the residential building you live in?*
  - *under 5 years*
  - *5–20 years*
  - *20–50 years*
  - *over 50 years*
- *What floor do you live on? If you live on a particular floor of a building/house, select the option "other" and enter the number of the floor you live on.*
  - *basement*
  - *ground floor*
  - *top floor*
  - *other* ____________________
- *Your apartment/house is oriented towards (it is possible to check more than one answer):*
  - *north*
  - *south*
  - *east*
  - *west*
- *The residential building you live in is constructed of:*
  - *bricks*
  - *stone*
  - *concrete/reinforced concrete*
  - *wood*
  - *other* ____________________
- *The colour of the façade of the residential building where you live is:*
  - *light (e.g., white, beige, light grey)*
  - *medium dark (e.g., yellow, orange, light blue, light brown)*
  - *dark (e.g., red, brown, dark grey, black…)*
  - *other* ____________________
- *The windows in the residential building where you live in are:*
  - *old, one-layer or two-layer*
  - *new, thermally insulated two-layer*
  - *new, thermally insulated three-layer*
  - *other* ____________________
- *Has the building or apartment you live in been renovated so far with the aim of improving energy efficiency (new façade, new windows, etc.)? If your answer is yes, select the "other" option and describe what was renovated.*
  - *yes*
  - *no*
  - *other* ____________________

Overheating prevention

- *Which of the following building-level overheating prevention measures have been implemented in your building:*
  - *external blinds/curtains (e.g., blinds, shutters, awnings)*
  - *internal blinds/curtains (e.g., textile blinds)*
  - *solar protective glass on the windows (e.g., tinted or reflective glass)*
  - *thermal insulation of the building envelope (external walls, roof, windows)*
  - *the possibility of natural ventilation at night (open the windows)*
  - *greening of the building envelope (e.g., green roof, green façade)*
  - *greenery in the immediate vicinity of the building (e.g., tall trees with a dense canopy)*
  - *air conditioner*
  - *ceiling or mobile fans*
  - *other* ____________________
- *Which of the following measures do you think would be adequate to implement on the level of the building (and are currently not present):*
  - *external blinds/curtains (e.g., blinds, shutters, awnings)*
  - *internal blinds/curtains (e.g., textile blinds)*
  - *solar protective glass on the windows (e.g., tinted or reflective glass)*
  - *thermal insulation of the building envelope (external walls, roof, windows)*
  - *the possibility of natural ventilation at night (open the windows)*
  - *greening of the building envelope (e.g., green roof, green façade)*
  - *greenery in the immediate vicinity of the building (e.g., tall trees with a dense canopy)*
  - *air conditioner*
  - *ceiling or mobile fans*
  - *other* ____________________
- *Which of the following measures do you use to prevent overheating before turning on the air conditioner, if you have one?*
  - *extending the external blinds/curtains*
  - *extending the internal blinds/curtains*
  - *natural ventilation (opening the windows) at night*
  - *natural ventilation (opening the windows to create ventilation) in the daytime*
  - *turning on a ceiling or mobile fan*
  - *none of the above*
  - *other* ____________________

Appendix B

Table B1

Current climate and population characteristics of the Montenegro municipalities arranged according to T_L.

Municipality	T_L [°C]	Jan [°C]	Feb [°C]	Mar [°C]	Apr [°C]	May [°C]	Jun [°C]	Jul [°C]	Aug [°C]	Sep [°C]	Oct [°C]	Nov [°C]	Dec [°C]	HDD_{10} [Kday]	CDD_{18} [Kday]	Köppen Geiger	ASHRAE	Elevation [m]	Population (2023 census)	Population share [%]
Plav	5.62	-2.5	-2.1	-0.6	2.7	8.8	15.2	15.0	15.7	10.0	4.8	3.7	-3.8	2138	11	Dfb	6A	958	10378	1.6
Mojkovac	5.85	-2.8	-4.2	-1.4	7.3	9.3	12.8	15.9	13.7	12.2	6.3	1.8	-1.4	2026	19	Dfb	6A	810	6824	1.1
Gusinje	6.05	-1.1	-2.5	-1.3	3.6	8.2	13.1	15.7	17.2	11.2	5.9	4.8	-2.7	2019	49	Dfb	6A	925	4662	0.7
Rožaje	6.08	-1.7	-6.3	-0.9	8.1	8.6	12.7	15.9	16.3	11.4	7.5	3.4	-2.9	2029	21	Dfb	6A	1041	25247	4.0
Kolašin	6.36	-1.0	0.3	0.9	2.8	9.7	12.3	15.9	17.2	10.9	6.8	2.1	-2.0	1898	38	Dfb	6A	956	6765	1.1
Plužine	6.46	-1.2	-5.1	-1.4	4.1	12.0	13.4	16.0	17.8	11.2	8.0	4.6	-2.7	1974	57	Dfb	6A	749	2232	0.4
Šavnik	6.54	-1.1	-4.7	-1.3	6.3	11.3	15.4	16.1	17.3	11.3	6.0	4.2	-3.1	2019	55	Dfb	6A	825	1588	0.3
Žabljak	6.72	-1.5	0.9	0.1	5.5	10.4	12.8	15.4	15.8	13.0	8.3	3.3	-3.8	1816	15	Dfb	6A	1451	3002	0.5
Pljevlja	7.21	-2.9	-3.1	-0.3	9.2	14.0	14.8	16.3	15.4	12.6	8.9	4.3	-3.4	1782	13	Dfb	5A	773	24542	3.9
Berane	7.28	-0.2	-5.3	1.9	8.0	13.4	13.8	17.7	17.2	10.6	6.7	4.3	-1.6	1757	47	Dfb	5A	671	25162	4.0
Petnjica	7.36	-3.2	-0.7	2.1	9.2	11.9	14.3	17.2	17.6	15.0	6.4	2.2	-4.0	1812	51	Dfb	5A	725	5552	0.9
Andrijevica	7.57	-2.4	-0.9	1.2	5.6	11.1	15.0	17.9	18.4	16.7	6.7	2.7	-1.7	1833	99	Dfb	5A	787	3978	0.6
Bijelo Polje	8.76	1.0	-1.5	3.1	10.2	13.1	15.6	18.6	16.3	14.7	8.1	5.1	0.1	1415	83	Dfb	5A	594	39710	6.3
Nikšić	10.13	1.8	1.2	3.7	11.3	13.6	16.9	19.3	20.4	14.6	11.1	6.4	0.5	1156	219	Cfb	5C	632	66725	10.5
Kotor	12.63	3.0	3.1	8.8	10.0	17.0	19.8	21.6	23.0	18.9	12.8	8.8	4.0	733	384	Cfa	4A	4	21916	3.5
Tivat	12.76	4.5	3.1	8.8	10.0	17.0	19.0	22.4	23.0	17.1	12.8	10.6	4.0	673	387	Cfa	4A	2	16340	2.6
Cetinje	13.51	4.3	8.4	6.3	13.2	17.6	20.4	23.0	25.4	16.6	13.7	7.5	5.2	588	526	Cfa	4A	648	14465	2.3
Danilovgrad	13.71	5.1	4.9	8.7	12.5	17.3	21.9	24.0	24.4	17.8	14.3	10.3	2.7	623	562	Cfa	4A	57	18832	3.0
Tuzi	13.75	4.1	1.2	7.0	12.8	19.9	21.6	25.0	25.7	22.2	13.8	7.3	3.6	837	797	Cfa	4A	47	13142	2.1
Herceg Novi	13.84	2.0	5.2	10.7	11.6	17.6	19.7	22.7	23.8	21.6	13.7	11.6	5.4	566	540	Cfa	4A	30	31471	5.0
Podgorica	14.17	4.6	1.5	9.6	13.8	17.2	22.1	25.7	26.8	19.3	14.4	7.8	6.3	653	734	Cfa	4A	48	180186	28.5
Budva	14.90	6.9	6.9	11.2	11.8	18.8	20.7	24.1	24.7	21.7	14.8	9.5	7.1	330	662	Cfa	3C	23	26667	4.2
Zeta	16.34	5.5	8.6	12.8	16.3	19.6	24.3	25.5	29.1	21.0	16.6	8.8	7.4	337	947	Cfa	3A	11	16206	2.6
Ulcinj	16.67	8.3	8.8	13.3	15.7	20.4	22.3	25.8	26.2	20.0	17.4	11.5	9.6	158	780	Cfa	3A	13	21395	3.4
Bar	17.12	8.7	11.2	13.2	15.1	18.4	21.9	25.0	25.8	21.1	18.0	15.9	10.7	74	735	Cfa	3A	5	46171	7.3

Lowest value	50th percentile	Highest value

Table B2

Future projected climate and population characteristics of the Montenegro municipalities arranged according to T_L.

Municipality	T_L [°C]	Jan [°C]	Feb [°C]	Mar [°C]	Apr [°C]	May [°C]	Jun [°C]	Jul [°C]	Aug [°C]	Sep [°C]	Oct [°C]	Nov [°C]	Dec [°C]	HDD_{10} [Kday]	CDD_{18} [Kday]	Köppen Geiger	ASHRAE	Elevation [m]	Population (2050 projections)	Population share [%]
Plav	10.35	2.8	1.4	3.1	6.2	12.8	20.5	21.5	22.6	15.6	10.1	7.3	-0.3	1335	431	Dfa	5A	958	6435	1.2
Mojkovac	10.65	2.5	-0.6	2.5	10.9	13.3	18.1	22.5	20.6	17.8	11.7	5.4	2.3	1285	438	Dfa	5A	810	4232	0.8
Gusinje	10.77	4.1	1.0	2.5	7.1	12.3	18.4	22.2	24.1	16.7	11.2	8.4	0.7	1227	474	Cfa	5C	925	2891	0.5
Rožaje	10.88	3.8	-2.7	2.9	11.7	12.6	18.0	22.4	23.2	17.0	12.9	7.1	0.7	1308	507	Dfa	5A	1041	15656	2.9
Kolašin	11.12	4.3	3.8	4.7	6.3	13.7	17.6	22.5	24.0	16.4	12.2	5.7	1.5	1111	472	Cfa	4A	956	4195	0.8
Plužine	11.28	4.1	-1.6	2.4	7.6	16.1	18.8	22.8	24.8	16.9	13.3	8.1	1.0	1280	539	Dfa	4A	749	1384	0.3
Šavnik	11.33	4.2	-1.2	2.5	9.8	15.4	20.8	22.8	24.2	16.9	11.3	7.7	0.5	1245	592	Dfa	4A	825	985	0.2
Žabljak	11.54	3.9	4.5	3.9	9.1	14.4	18.2	22.1	22.8	18.7	13.7	6.8	-0.1	1064	481	Dfa	4A	1451	1862	0.3
Berane	12.06	5.2	-1.7	5.8	11.5	17.4	19.1	24.2	24.1	16.2	12.0	7.9	2.0	1067	588	Dfa	4A	671	15603	2.9
Pljevlja	12.07	2.6	0.6	3.6	12.8	18.0	20.2	23.0	22.3	18.2	14.3	7.8	0.5	1175	572	Cfa	4A	773	15219	2.8
Petnjica	12.16	2.2	2.9	5.9	12.7	15.9	19.6	23.7	24.5	20.6	11.7	5.8	-0.3	1127	658	Dfa	4A	725	3443	0.6
Andrijevica	12.32	3.0	2.7	5.0	9.2	15.1	20.3	24.4	25.2	22.2	12.0	6.3	1.9	1085	722	Cfa	4A	787	2467	0.5
Bijelo Polje	13.58	6.4	2.2	7.0	13.8	17.1	20.9	25.1	23.2	20.3	13.5	8.6	3.9	805	729	Cfa	4A	594	24624	4.5
Nikšić	14.84	7.0	4.6	7.4	14.8	17.6	22.3	26.1	27.4	20.2	16.3	9.9	3.9	642	931	Cfa	4A	632	64983	12.0
Kotor	17.17	7.8	6.4	12.3	13.5	21.0	24.9	28.1	29.8	24.2	17.8	12.2	7.1	348	1265	Bsk	3B	4	18923	3.5
Tivat	17.29	9.2	6.4	12.3	13.5	21.0	24.2	29.0	29.8	22.3	17.8	14.1	7.1	314	1227	Bsk	3B	2	14109	2.6
Cetinje	18.07	9.2	11.6	9.8	16.6	21.7	25.6	29.6	32.3	21.9	18.8	10.9	8.3	224	1358	BSh	3B	648	14087	2.6
Herceg Novi	18.34	6.7	8.4	14.1	15.0	21.6	24.8	29.2	30.5	26.9	18.7	15.0	8.5	253	1437	BSh	3B	30	27174	5.0
Danilovgrad	18.37	10.2	8.3	12.3	15.9	21.4	27.1	30.7	31.4	23.3	19.5	13.7	5.9	316	1512	BSh	3B	57	18340	3.4
Tuzi	18.37	9.1	4.5	10.6	16.2	23.9	26.8	31.6	32.6	27.6	19.0	10.8	6.7	461	1737	BSh	3B	47	12799	2.4
Podgorica	18.81	9.6	4.8	13.1	17.3	21.3	27.3	32.3	33.7	24.8	19.5	11.2	9.5	338	1685	BSh	3B	48	175483	32.4
Budva	19.40	11.6	10.1	14.6	15.2	22.8	25.8	30.6	31.5	26.9	19.8	12.9	10.1	102	1585	BSh	3B	23	23026	4.2
Zeta	20.94	10.4	11.9	16.3	19.7	23.7	29.5	32.1	36.0	26.4	21.7	12.3	10.5	140	2037	BSh	2B	11	15783	2.9
Ulcinj	21.11	12.9	11.9	16.6	19.1	24.4	27.4	32.2	33.0	25.2	22.5	14.9	12.4	41	1814	BSh	2B	13	18473	3.4
Bar	21.60	13.4	14.3	16.6	18.5	22.4	26.9	31.5	32.7	26.3	23.1	19.4	13.6	8	1792	BSh	2B	5	39866	7.4

Lowest value	50th percentile	Highest value

Data availability

Data will be made available on request.

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