Impact of global warming on the potential for passive solar heating and overheating of buildings in Montenegro

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Abstract

Montenegrin building stock is highly energy inefficient, while the country has a high potential for using solar energy. Therefore, the potential for implementing passive solar heating and overheating in residential buildings was assessed in four locations among the country's three climate zones, namely the Coastal zone, the Continental zone and the Mountain zone, for the current climate and two different climate change scenarios (SSP2-4.5 and SSP5-8.5). Besides, the need for overheating prevention measures was assessed as well. The results demonstrated a relatively high potential for applying passive solar heating in Montenegrin buildings in current and future climate conditions, especially in the Mountain zone. At the same time, the need for overheating prevention measures is projected to increase under global warming the most in the Continental climate zone. The locations in this zone are the most vulnerable to overheating because they will potentially shift from heating-dominated to cooling-dominated, depending on the climate change scenario. Therefore, because of the high climate variability in Montenegro, building design approaches and policies should be addressed accordingly.

Keywords: passive solar heating, overheating, buildings, global warming, Montenegro. energy efficiency

1. Introduction

Montenegro is located in the western Balkans and has been among Europe's most inefficient energy consumers. Its process of negotiations for EU accession is open. Thus, energy efficiency improvement is considered a strategic goal at the national level. Improving the energy efficiency of building stock will have political and economic implications for Montenegro, given that about 2/3 of thermal energy use in households is covered by electricity, and 1/3 of all electricity is provided by imports. Detached houses in Montenegro represent 83.7 per cent of building stock. At the same time, their average annual heating demand is 276.50 kWh/m^2, the average annual domestic hot water demand is 31.9 kWh/m^2, and the annual cooling demand is 74.0 kWh/m^2 (Navikova et al., 2015). The average number of yearly heating degree days (HDD) in Montenegro is 2386 Kdays (Ministry of Economy, 2013). Unlike many other countries in the region, Montenegro does not have a district heating system or gas network and residential buildings are primarily heated using solid fuels or electricity. On the other hand, Bajat et al. (2020) stated that Montenegro is one of the European countries with the highest potential for the development, production, and consumption of solar energy, with an average annual potential insolation of 1800 kWh/m² and more than 2000 annual hours of sun. Therefore, implementing passive solar architecture and solar collectors for heating buildings or photovoltaics for electricity production should have excellent potential. Due to the country's concurrent high energy inefficiency and a high potential for using solar energy, the study aimed to assess the potential for implementing passive solar heating (PSH) in residential buildings, which was assessed for two different climate change scenarios.

2. Methods

2.1. Locations and climate

According to Navikova et al. (2015), Montenegro is divided into three climate zones: Zone 1: Coastal zone (Mediterranean climate, average annual HDD = 1623 Kdays, Bar, Budva, Danilograd, Herceg Novi, Kotor, Podgorica, Tivat, and Ulcinj), Zone 2: Continental zone (temperate climate, average annual HDD = 2528

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Kdays, Nikšić and Cetinje) and Zone 3: Mountain zone (continental climate with cold winters, average annual HDD = 3388 Kdays, Andrijevica, Berane, Bijelo Polje, Žabljak, Kolašin, Mojkovac, Plav, Plužine, Pljevlja, Rožaje, Šavnik). However, a significant part of the country has a mild Mediterranean climate, while concurrently, the mountainous part is less populated. In particular, about 2/3 of residential buildings are located in Zone 1, with more than 30 per cent of the country's population in Podgorica alone. Roughly 25 per cent of the population lives in Zone 3, and only about 11 per cent in Zone 2 (Navikova et al., 2015). Therefore, the study included four locations, namely Podgorica and Ulcinj (Zone 1), Nikšić (Zone 2) and Žabljak (Zone 3) (see Table 1 and Figure 1). The selected locations' climate files (EPW based on TMY 2004–2018) were collected from the Repository of free climate data for building performance simulation (Climate.OneBuilding, 2023). Furthermore, future climate files considering global warming were morphed using the Future Weather Generator (Rodrigues et al., 2023). The future climate files were morphed per the IPCC's Shared Socioeconomic Pathways (SSP) scenarios SSP2-4.5 (intermediate greenhouse gas – GHG emissions) and SSP5-8.5 (very high GHG emissions) and 2036–2065 and 2066–2095 timeframes.

Tab. 1: Analysed locations (also see Figure 1)

Climate zone	Location	ASHRAE climate zone	Köppen-Geiger climate	Latitude	Longitude	Elevation
Zone 1	Ulcinj	3A	Cfa	41°55' N	19° 14' E	29 m
Zone 1	Podgorica	3A	Cfa	42° 26' N	19° 17' E	50 m
Zone 2	Nikšić	4A	Cfa	42° 46' N	18° 57' E	647 m
Zone 3	Žabljak	6A	Dfb	43° 9' N	19° 38' E	1450 m

Fig. 1: Climate zones of Montenegro with the analysed locations

2.2. Potential for passive solar heating

The potential for PSH was assessed using the BcChart v2.3 tool (Košir and Pajek, 2021). The tool uses the upgraded Olgyay's bioclimatic chart, considering the outdoor air temperature, relative humidity and solar radiation intensity to determine if human thermal comfort in a generic building may be achieved at certain outdoor conditions. Besides, potential passive building design measures are proposed when human thermal comfort is unmet. In particular, for this study, the comfort achieved by solar radiation utilisation (C_{sn}) and the potential for PSH (R) values were considered, which were summed up to represent the cumulative PSH potential (P_{PSH}) of a location and expressed as the number of days per year. Additionally, the number of days when shading is needed (S_h) and the number of days when thermal comfort is achieved by solar control (C_z), either shading or solar utilisation, was determined for each location. All the above-stated values were determined using the average, maximum and minimum daily outdoor temperature, relative humidity and solar irradiance for each month. The exact methodology used by the BcChart tool is presented in the paper by Košir and Pajek (2017).

2.3. Implications for energy-efficient building design

In the last step, the results were evaluated in the context of implications for energy-efficient building design using degree hours as a generic proxy for building energy performance. Although the use of degree hours (or degree days) for estimating the energy efficiency of a large and averaged sample of buildings is a well-established top-down method, it has limitations due to being based solely on the external temperature and a presumed building base temperature (Košir, 2019). Nevertheless, the degree hours method can be used to approximate the impact of climate and climate change on the average building's energy use for heating and cooling (Dirks et al., 2015; Clarke et al., 2018). For this reason, yearly values of heating degree hours (HDH) and cooling degree hours (CDH) were calculated using equations 1 and 2.

$$\mathrm{HDH} = \sum_{i=1}^{8760} \left(T_{b,H} - T_{o,i}\right)^{+} \quad \text{if } \mathrm{T_{b,H}} - \mathrm{T_{o,i}} > 0 \qquad \text{(eq. 1)}$$

$$\mathrm{CDH} = \sum_{i=1}^{8760} \left(T_{b,C} - T_{o,i}\right)^{+} \quad \text{if } \mathrm{T_{o,i}} - \mathrm{T_{b,C}} > 0 \qquad \text{(eq. 2)}$$

$T_{b,H}$ is the heating base temperature equal to 10 °C and $T_{b,C}$ is the cooling base temperature equal to 23 °C. $T_{o,i}$ represents the outdoor air temperature at the i-th hour of the year. Only the positive differences between T_b and $T_{o,i}$ are considered. The corresponding heating and cooling base temperatures were defined so that the results of HDH and CDH are representative for newly built or recently energy-renovated buildings.

3. Results and Discussion

3.1. Potential for passive solar heating

Figure 2 shows the P_{PSH} in days per year at each studied location, indicating the annual occurrence of environmental conditions allowing for PSH. Namely, the number of days when solar radiation is adequate to ensure passive solar heating is given. At current climate conditions (i.e. 2004–2018), the location with the highest P_{PSH} of 194 days annually is Žabljak (Zone 3 – i.e. cold climate), which was expected. On the other hand, Podgorica (Zone 1 – i.e. Mediterranean climate) has the lowest P_{PSH} at only 145 days annually. Nevertheless, all the analysed locations show a relatively high $P_{PSH,}$ and solar energy may be utilised up to 50 per cent of the year to provide indoor thermal conditions. In particular, in Žabljak, the highest P_{PSH} is achieved between April and October, while solar radiation is insufficient between November and March. Thus, heat retention and conventional heating are necessary during the specified period. In Žabljak, global warming is projected to decrease the P_{PSH}, mainly between June and September (due to overheating occurrence), especially in the SSP5-8.5 emission scenario. In the latter's case, the P_{PSH} would be reduced by 36 days (18.5 per cent relative to 2004–2018). Similar behaviour, although less pronounced, may be observed for Nikšić. In contrast, under global warming (SSP5-8.5), P_{PSH} is projected to decrease and later increase (due to increased winter temperatures) even above the current values in Ulcinj and Podgorica. In Ulcinj, P_{PSH} values are projected to increase to the extent that they would be even higher than in Žabljak and Nikšić until the end of the century. The range of the projected P_{PSH} at the analysed locations would be 137–184 days in the SSP2-4.5 scenario and 149–164 days in the SSP5-8.5 scenario.

Although the potential for passive solar heating is not expected to change under global warming in the analysed locations significantly, the effects of global warming need to be evaluated in the context of overheating occurrence. Therefore, the number of days when shading is needed was assessed at all the locations. Observing data in Figure 3, it can be seen that the importance of shading (i.e. overheating prevention) is projected to increase significantly. At current climate conditions, locations in Zone 1 have the highest shading need, with 135 days in Podgorica and 121 days in Ulcinj. The intermediate shading need of 54 days is observed in Nikšić

(Zone 2). At the same time, Zone 3 (Žabljak) has the lowest shading need at 0 days annually. As expected, the need for shading is expected to increase over time due to the effects of global warming, with the highest projected increase of 86 days in Nikšić (SSP5-8.5) at the end of the century. Therefore, the results highlight the increased importance of overheating prevention (i.e. shading) even if the P_{PSA} is not projected to change significantly.

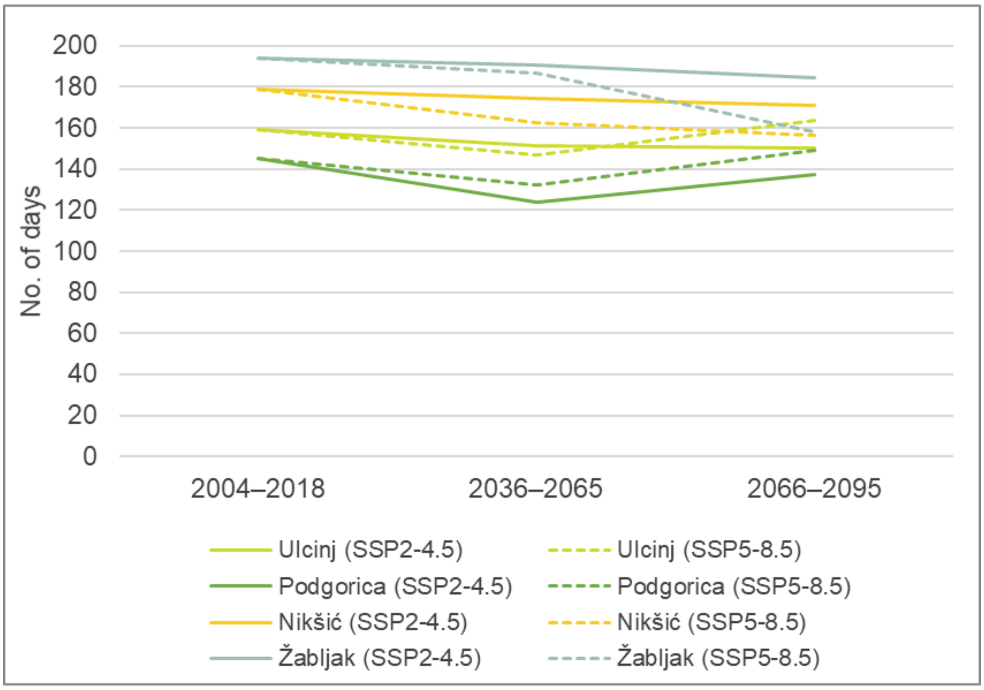

Fig. 2: Potential for passive solar heating in the analysed locations for current and two future periods. The potential is expressed in the number of days when solar radiation is adequate to ensure passive solar heating

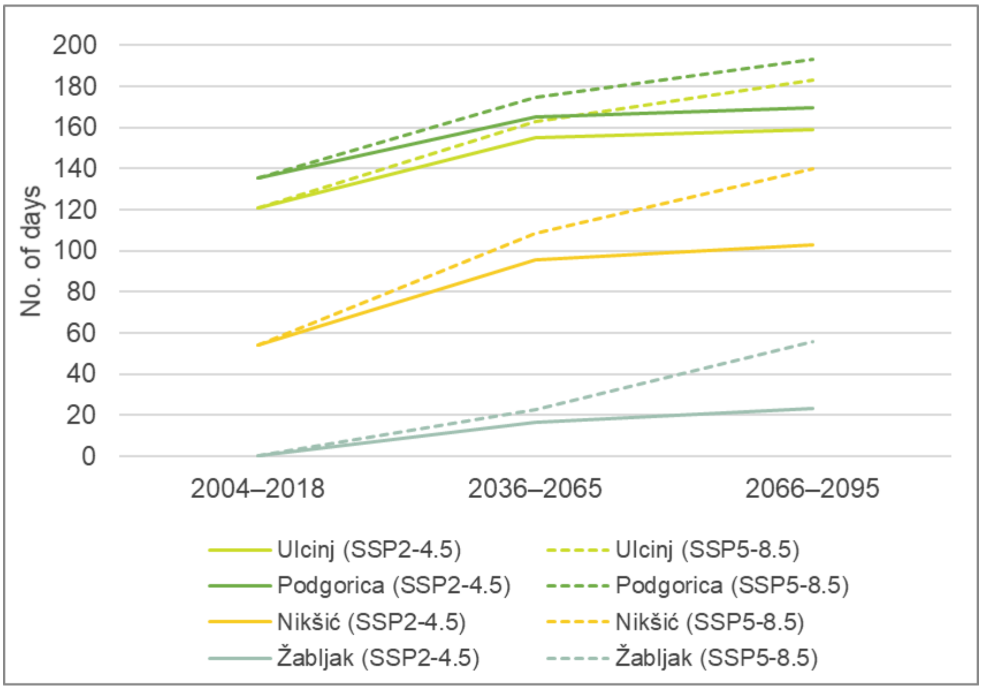

Fig. 3: Shading potential in the analysed locations for current and two future periods. The potential is expressed in the number of days when shading is needed to ensure thermal comfort

Moreover, the thermal comfort potential was assessed when comfort could be assured by solar energy control, either shading or solar harvesting, to understand how global warming affects the time when no additional passive measures are needed (i.e. free-run operation of buildings). Figure 4 shows that in Zone 1, the number of days when free-run comfort is achieved is projected to decrease significantly, especially in Ulcinj (i.e. by 35 days for SSP5-8.5 compared to the 2004–2018 period). On the other hand, Nikšič (Zone 2) and Žabljak (Zone 3) exhibit an increase in free-run comfort potential, with the highest increase of 51 days for SSP5-8.5 relative to 2004–2018 in Žabljak.

The projected changes in the bioclimatic potential of the analysed locations indicate that building design in the three Montenegrin climatic zones should focus on implementing overheating prevention measures while preserving passive solar heating actions. The latter's importance will remain high, which, in conjunction with the increased importance of overheating prevention, represents a challenge for the passive design of buildings under the future projected climates. The results align with the findings of the study by Pajek and Košir (2022) conducted for Podgorica under RCP4.5 and RCP8.5 climate change scenarios. Building designers should consider climate adaptation to minimise energy use and increase occupant thermal comfort. Therefore, in section 3.2, implications for energy-efficient building design are discussed.

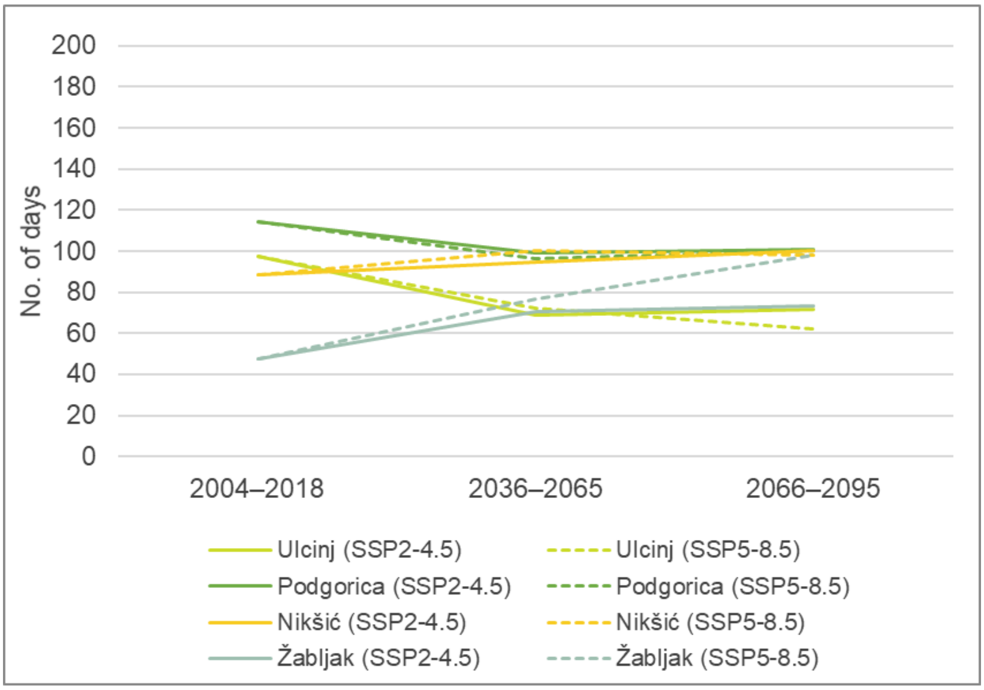

Fig. 4: Comfort potential in the analysed locations for current and two future periods. The potential is expressed in the number of days when comfort can be assured by solar energy control (either shading or solar harvesting)

3.2. Implications for energy-efficient building design

Concurrently with the bioclimatic analysis presented in the previous chapter, the evaluation of climate change impacts on energy use in the analysed locations and zones was evaluated. HDH and CDH were calculated using the original (i.e. 2004–2018) and morphed climate files for both climate change scenarios. The results presented in Figures 5 (SSP2–4.5) and 6 (SSP5–8.5) underscore the conclusions of the bioclimatic analysis. Furthermore, the calculated values of HDH and CHD more clearly illustrate the projected changes for energy use in average buildings of the analysed locations.

The analysis shows a similar trend for both climate change scenarios, which is a general reduction in annual HDH for all locations and an increase in the annual value of CDH (Fig. 5 and 6.). The presented data also clearly indicates the difference between climate Zone 1 and Zones 2 and 3, as the locations of Podgorica and Ulcinj will exhibit a disproportionate increase in CDH compared to a decrease in HDH. In general, this means that the cumulative value of HDH and CDH is expected to increase in Zone 1 and decrease in Zones 2 and 3. In particular, the most considerable impact of climate change is projected for Podgorica as by the end of the century the CDH is expected to increase by 11131 Kh (91 per cent increase) for SSP2–4.5 and 22559 Kh (185 per cent increase) for SSP5–8.5 scenario relative to 2004–2018. Simultaneously, the HDH will decrease by 55 and 85 per cent for SSP2–4.5 and SSP5–8.5 scenarios, respectively, resulting in an overall increase of energy needed for cooling and heating (Fig. 5. and 6.). The same trend is also actual for Ulcinj, although with a more minor overall expected energy use for cooling.

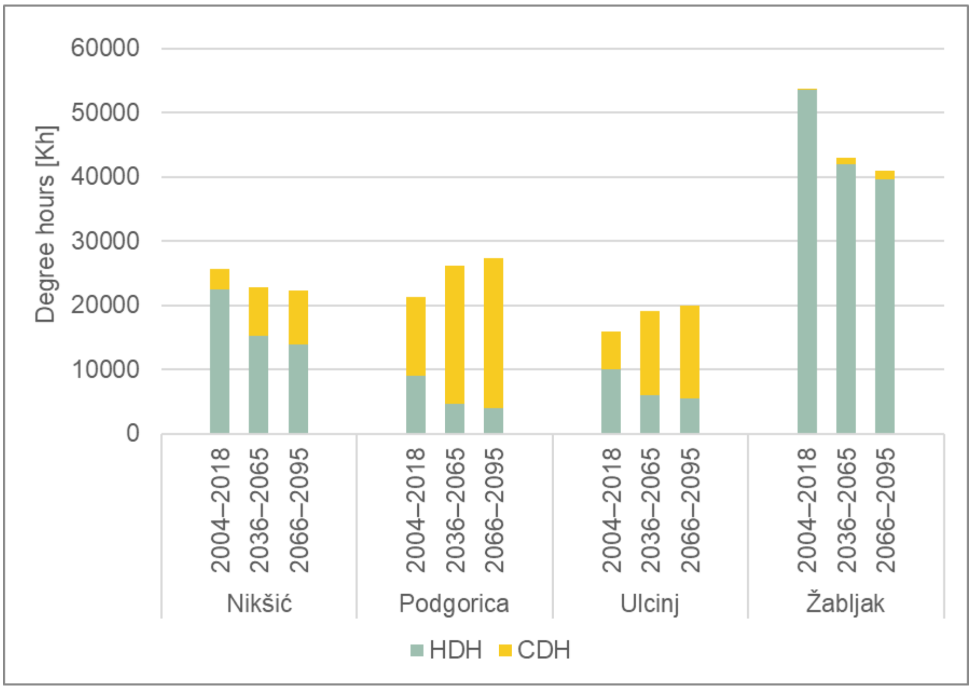

Fig. 5: Heating (HDH) and cooling degree hours (CDH) under current and SSP2–4.5 climate change scenario

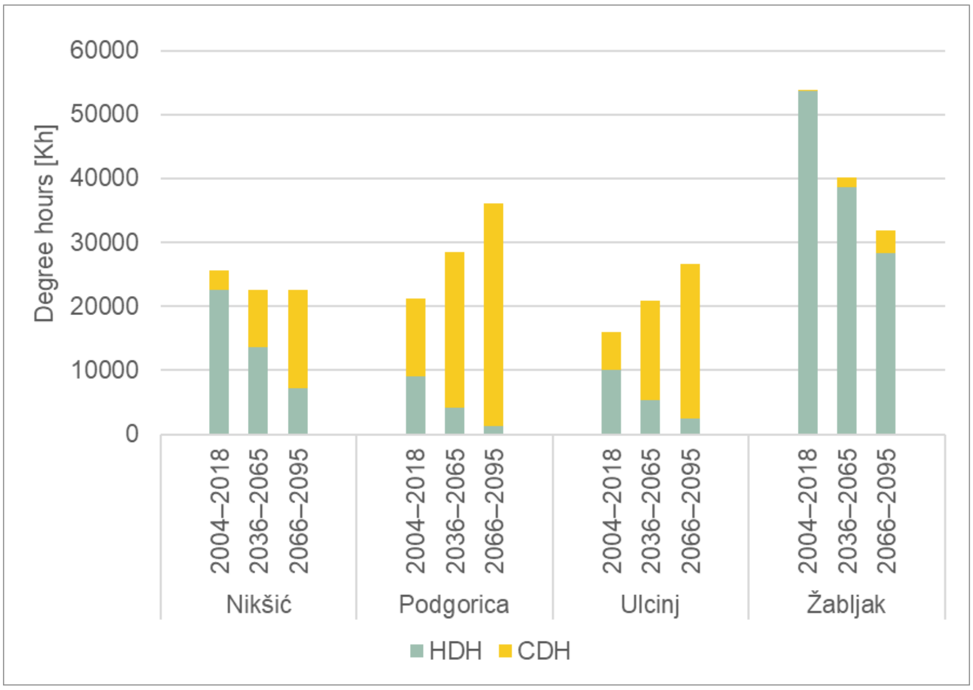

Fig. 6: Heating (HDH) and cooling degree hours (CDH) under current and SSP5–8.5 climate change scenario

Contrasting the impact of global warming in Zone 1 are the outcomes for Nikšić and Žabjak. As illustrated in Figures 5 and 6, these locations will generally benefit from projected climate change as the cumulative value of HDH and CDH is projected to decrease under both scenarios. Particularly for Žabjak, the projected impact is substantial as the HDH is expected to decrease by 13969 Kh (26 per cent decrease) for SSP2–4.5 and 25217 Kh (47 per cent decrease) for SSP5–8.5, with relatively small increases in CDH. The case of Nikšić is less straightforward as the increase in the cooling need is substantially conditioned by the climate change scenario in question. This means that under the SSP2–4.5 scenario, the location of Nikšić will remain heating-dominated (i.e. HDH > CDH, see Fig 5.) at the end of the century, while under the SSP5–8.5, it will become cooling-dominated (i.e. HDH < CDH, see Fig. 6). However, regardless of the considered scenario the overall sum of HDH and CDH for Nikšić is projected to decline and remain comparable among considered climate change scenarios up to the end of the 21st century.

4. Conclusions

The potential for passive solar heating in Montenegro is projected to be affected by global warming. In particular, the locations in the Continental and Mountain climate zones (i.e. Zones 2 and 3, respectively) might face a reduction of the potential because of higher spring–autumn air temperatures and solar radiation. On the contrary, the locations in the Coastal climate zone (i.e. Zone 1) would face a less significant potential reduction, while in specific scenarios, the potential for passive solar heating would even increase. On the other hand, locations in the Coastal zone have the highest and ever-increasing need for overheating prevention measures, while the need is projected to increase under global warming the most in the Continental zone. Overall, it may be concluded that passive solar heating has a relatively high potential for application in buildings in Montenegro, which is, on the country's average, not expected to decrease significantly due to global warming. However, in the context of energy-efficient building design and overheating vulnerability, the implications of global warming need to be addressed. In this manner, the locations in Continental zone are the most vulnerable to overheating because buildings in this zone will potentially shift from heating-dominated to cooling-dominated, depending on the climate change scenario.

Furthermore, the results of the presented analysis point to the fact that although Montenegro is geographically a small country, it is exceptionally climatically varied. Consequentially, such variability should be addressed at the level of building design approaches and legislative regulation, as is underscored by the differences between the Coastal and Mountain zones. Furthermore, the projected climate change will represent an additional challenge for energy-efficient and climate-adapted building design, particularly for Continental climate zone locations like Nikšić. At such locations, depending on the climate change scenario, buildings might become cooling-dominated in the second half of the century, necessitating a substantial shift in the design approaches. This is especially important because occupants have limited awareness about the potential of passive measures when summer thermal discomfort is the dominant issue (Pajek et al., 2023).

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