Overheating vulnerability assessment of energy retrofit actions in a multi-apartment building in Podgorica, Montenegro

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Abstract. The study aimed to assess the overheating vulnerability of an existing multi-apartment building built in 1971 in Podgorica, Montenegro. The building consists of 80 apartments and is mostly still in its original state. Firstly, the building was modelled in EneryPlus, and a parametric study was performed with jEPlus. The energy need for heating and cooling was simulated using parameters such as thermal insulation level, window properties, external surface solar absorptivity, shading activation set-point, and natural ventilation cooling intensity. Moreover, the energy need was determined for four different climate periods, namely for the current and three future periods up to the end of the 21st century under the RCP8.5 climate change scenario. The total number of building models equalled 648 for each of the four climate scenarios, resulting in 2,592 simulated cases. After that, the overheating vulnerability score was determined using the minimax regret method and cooling energy need as a performance indicator. The best retrofit action was determined by identifying the most favourable combination of the overheating vulnerability and total energy need. The results deliver the appropriate energy retrofit actions to limit the increase in overheating risk and provide for climate change adaptation of the multi-apartment building stock in Montenegro.

1 Introduction

Montenegro is a country in south-eastern Europe currently negotiating accession to the European Union (EU). According to the 2021 report [1], the residential sector in Montenegro is responsible for about one-third of total energy use, primarily due to high energy inefficiency. Therefore, numerous national and EU documents recognise energy efficiency improvement and climate change adaptation as key priorities for achieving sustainable development [2,3]. Therefore, improving energy efficiency in new and existing buildings is the country's strategic priority. In particular, the Secretariat's Discussion Paper on Riding the Renovation wave in the Western Balkans [3] exposed significant potential for energy savings in Montenegrin multi-apartment buildings, which account for a 39-per-cent share of residential buildings.

However, global warming is projected to affect the choice of energy retrofit measures [4] because it will decrease heating and increase cooling energy needs in residential buildings [5]. In this context, Pajek and Košir [6] demonstrated that a significant increase in building overheating could be expected in Podgorica (Montenegro) considering RCP4.5 and RCP8.5 climate change scenarios. Notably, the study showed that under the RCP8.5 scenario, the period when overheating prevention measures are needed is projected to increase by about two months by the end of the century compared to the present climate. Similarly, Rodrigues and Fernandes [7] assessed the current and future overheating risk for residential buildings in Podgorica. They concluded that cooling demand would increase irrespective of the thermal transmittance of the building envelope and that design measures, such as shading, smaller windows and appropriate orientation, must be considered in energy efficiency improvement measures.

Moreover, concerning the climate change impacts Tootkaboni et al. [8] emphasised that appropriately retrofitted buildings are less sensitive to global warming. Similarly, Pajek and Košir [9] showed that extremely high overheating vulnerability is not expected in very energy-efficient residential buildings, especially when overheating prevention measures are added.

All in all, it could be concluded that a vast share of Montenegrin building stock needs energy retrofit and that global warming must be considered in energy retrofit actions in order to assure climate adaptability. Therefore, the present study aimed to assess the overheating vulnerability of various retrofit actions under different climate scenarios using the case of an existing energy-inefficient multi-apartment building in Montenegro. The latter was selected to address the specifics of the Montenegrin building stock. The overheating vulnerability and energy efficiency assessment was used to evaluate the potential of several energy retrofit actions.

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2 Methods

2.1 Location, climate and building

The sample multi-apartment building is located in Podgorica, Montenegro (42° 26’ N, 19° 16’ E, 42 m AMSL, also see Figure 1). According to the Köppen-Geiger climate classification, Podgorica has a Cfa (humid subtropical) transitioning to Csa (Mediterranean) climate.

Fig. 1. Macro- and micro-location of the sample building.

The sample multi-apartment building (see Figure 1) is an example of 15 buildings with the same shape and orientation, all part of a larger residential area consisting of similar buildings. The sample building was built in 1971, has 80 apartments, and is 92 m long, 13 m wide, and 20 m high. The standard floor-to-ceiling height is 2.64 m. The total conditioned floor area (A_u) of the building is 5,490.35 m^2. Its conditioned volume is 16,745.56 m^3, while the building shape factor f_s equals 0.34 m^{-1} (the ratio between the thermal envelope area and the building volume). Its longer façades face southwest and northeast (15° offset), and the roof is flat. The window-to-wall ratio (*WWR*) is 0.38. The construction and window thermal properties are presented in Table 1. However, the specific heat transmission thermal loss coefficient H'_T is 1.64 W/m^{2}K for the entire building envelope and 1.60 W/m^{2}K for the opaque part.

Table 1. Construction and window thermal properties.

Building element	***U* value [W/m^{2}K]**
Ground floor	2.57
Internal floor	0.72
External wall	1.58
Internal wall	1.63
Flat roof	0.69
Window[1]	1.80 (*SHGC* = 0.65)

[1] a typical/average window

Based on the data above, the building was modelled in DesignBuilder (Figure 1) and simulated with EnergyPlus. Set-point temperatures were 20 °C (heating) and 26 °C (cooling). The building is naturally ventilated. The combined infiltration and constant natural ventilation rates were set at 1.0 h^{-1}, 0.5 h^{-1} and 0.2 h^{-1} for April–October, November–March and unconditioned zones, respectively [10]. The internal heat gain rates were set at 3.0 W/m^2, 3.3 W/m^2 and 2.8 W/m^2 for appliances, lighting and occupants, respectively [10]. Shading is assured by fixed shading geometry, such as balconies, overhangs and vertical shading panels. Additional shading can be selected by the occupants through external or internal blinds. The shading set-point was assumed to be equal to 300 W/m^2 according to the ISO 13790 standard [11], while shading was active when the external temperature was above 24 °C. A detailed model description is presented in the paper by Pajek et al. [12].

2.2 Parametric study

A comprehensive parametric study was performed using jEPlus [13], and the selected parameters are presented in Table 2.

The climate-related parameters or climate files were selected to represent the current climate (i.e., 1982–1998) and three successive future projected climate periods (see Table 2). The current EPW file (i.e., 1982–1998) for Podgorica was sourced from EnergyPlus [14]. Furthermore, the study included climate change effects by considering the RCP8.5 emission scenario, usually discussed as a worst-case scenario concerning global warming. It describes a likely outcome if society does not prioritise cutting greenhouse gas emissions, offering a broader view of a world without future climate policy. Until the end of the century, the RCP8.5 scenario projects a radiative forcing of 8.5 W/m^2 and temperature increase over 3.5 °C compared to the preindustrial period. Three future projected EPW files for the RCP8.5 scenario were morphed using the Weather Shift tool [15]. However, it must be noted that using climate change scenarios to evaluate future building performance inherently includes uncertainties. Evaluating how well a specific scenario will describe actual future outcomes is impossible at present. Nevertheless, because the RCP8.5 scenario represents a worst-case outcome, it can be used to increase the robustness of buildings to climate change.

The building envelope- and operation-related parameters (see Table 2) were selected to reflect the existing building state or to represent the established or cost-effective retrofit actions.

Table 2. Parametric study parameters.

Parameter	No. of parameters	Parameter values
Opaque envelope thermal transmittance U_O [W/m^{2}K]	4	1.60 (existing)
		0.60
		0.40
		0.20
Window thermal transmittance U_W [W/m^{2}K]	3	1.80 (existing)
		1.20
		0.90
Window *SHGC* [-]	3	0.65 (existing)
		0.40
		0.20
External surface solar absorptivity α_{sol} [-]	2	0.40 (existing)
		0.20
Shading solar set-point SH_{SP} [W/m^2]	3	300 (existing)
		200
		100
Natural ventilation cooling rate *ACH* [h^{-1}]	3	0 (existing)
		1
		3
Total number of building models	**648**	
Climate file	4	1982–1998 (current)
		2026–2045 (RCP8.5)
		2056–2075 (RCP8.5)
		2080–2099 (RCP8.5)
Total number of simulated cases	**2,592**	

A detailed protocol of the parametric study is presented in the paper by Pajek et al. [12]. The annual energy need for heating (Q_{NH}) and cooling (Q_{NC}) as well as the total energy need Q_T (= Q_{NH} + Q_{NC}) were determined as building performance indicators.

2.3 Overheating vulnerability assessment

The overheating vulnerability was assessed using the robustness analysis method [16] based on the minimax regret theory presented by Savage [17]. The minimax regret method is based on the hypothesis that the decision-maker, knowing the consequences of a specific decision, might regret this decision and wish to have chosen another alternative in the decision-making phase. Thus, the most vulnerable building design has the highest regret concerning the energy performance achieved with the chosen criteria. The minimax regret method is described with Equations 1–3.

$$R_{max,i} = max(R_{i1}, R_{i2}, ..., R_{ij}) \qquad (1)$$

$$R_{ij} = PI_{ij} - A_j \qquad (2)$$

$$A_j = min(PI_{1j}, PI_{2j}, \ldots, PI_{ij}) \qquad (3)$$

$R_{max,i}$ is the maximum value of the performance indicator of the *i*-th building model. R_{ij} is the performance regret of the *i*-th building model in climate scenario *j*. A_j is the minimum value of the performance indicator in climate scenario *j,* and PI_{ij} is the performance indicator of the *i*-th building model in climate scenario *j*. The values of i = 1–648 and j = 1–4, as the parametric study contained 648 building models simulated under four different climate files. As a performance indicator (i.e., *PI*), for each building model in each future climate scenario (2026–2045, 2056–2075 and 2080–2099), the increment of annual cooling energy need (i.e., ΔQ_{NC}) relative to Q_{NC} in the 1982–1998 period was determined. Then, using Equation 4, the building model with the highest overheating vulnerability (and the lowest robustness) was identified.

$$V_{max} = max(R_{max,i}) \qquad (4)$$

V_{max} represents the most overheating-vulnerable combination of retrofit actions. Moreover, an overheating vulnerability score, the *OV* score, was determined by normalising the performance regret of each building model (i.e., R_{ij}) by the performance regret of the most vulnerable building model (i.e., V_{max}). Therefore, the range of the *OV* score is between 0 and 1. The combination with the lowest *OV* (i.e., equal to 0) was identified as the least vulnerable (i.e., the most robust), and the combination with the highest *OV* (i.e., equal to 1) was identified as the most vulnerable to overheating. Thus, the lower the *OV*, the more building resists overheating. The *OV* of the studied retrofit actions was evaluated according to ΔQ_{NC} in the 2080–2099 period.

3 Results and discussion

3.1 The existing building energy need

Firstly, the annual energy need for heating (Q_{NH}) and energy need for cooling (Q_{NC}) of the sample multi-apartment building in the existing state were observed under the current (i.e., 1982–1998) and the projected future climates.

Currently, the multi-apartment building is heating-dominated, meaning it needs more heating than cooling (see Figure 2). However, the climate under the RCP8.5 climate change scenario is projected to reverse the situation, and from the 2026–2045 period onward, the building would become cooling-dominated. Specifically, Q_{NC} would represent 55 %, 70 % and 79 % of Q_T in 2026–2045, 2056–2075 and 2080–2099, respectively (Figure 2). Accordingly, until the end of the 21st century, Q_{NC} of the analysed building is projected to be 3.6-times higher and Q_{NH} 2.3-times lower compared to the 1982–1998 period.

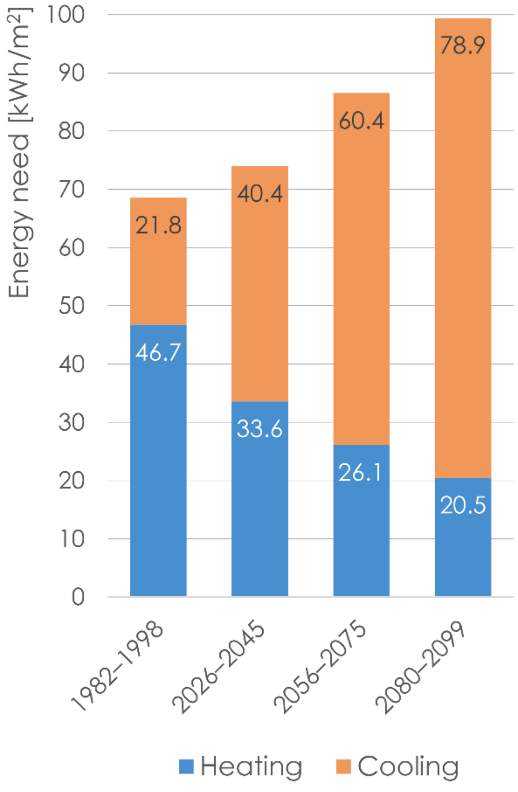

Fig. 2. Heating and cooling energy need of the existing building under four climate files.

3.2 Evaluation of energy retrofit actions

In this section, the effectiveness of different retrofit actions is discussed. Firstly, the retrofit actions were evaluated in the context of their ability to reduce Q_T under the current climate, i.e. in the 1982–1998 period. Table 3 presents the characteristic values of the best-performing 5 percent retrofit combinations.

Table 3. Characteristic energy need and parameter values of the best-performing 5 percent cases with the lowest Q_T under the current climate.

Value		mean	range
Energy need	Q_{NH} [kWh/m^2]	12.8	8.4–18.5
	Q_{NC} [kWh/m^2]	10.1	5.6–16.0
	Q_T [kWh/m^2]	22.9	17.5–25.7
Parameters	U_O [W/m^{2}K]	0.24	0.20–0.40
	U_W [W/m^{2}K]	1.05	0.90-1.80
	SHGC [-]	0.57	0.40–0.65
	α_{sol} [-]	0.30	0.20–0.40
	SH_{SP} [W/m^2]	144	100–300
	ACH [h^{-1}]	2.5	1.0–3.0

Observing Table 3, it is evident that energy retrofit of the considered building is necessary. On average, if one of the best-performing retrofit combinations were applied, the current Q_{NH} of the building would decrease by 60–82 % and Q_{NC} by 27–74 %. Such reduction of energy need may be achieved by using lower U_O and higher *ACH* than the building has in its existing state. However, other parameters may be left in their existing state (e.g., window and external surface properties, shading activation; see Table 3).

On the other hand, the worst-performing retrofit actions under current climate include leaving all the parameters at their current values, except *SHGC* and α_{sol}, which would be reduced to the lowest analysed values, i.e., 0.20. In this case, Q_{NH} of the building under current climate would be 67.8 kWh/m^2, Q_{NC} = 10.8 kWh/m^2, Q_T = 78.6 kWh/m^2 and *OV (*overheating vulnerability*)* = 0.58.

The overall best-performing combination of retrofit actions is achieved by insulating the opaque building envelope to U_O = 0.20 W/m^{2}K, upgrading the windows to U_W = 0.90 W/m^{2}K and *SHGC* = 0.65, leaving α_{sol} at 0.40 (light beige colour) and by actively using effective shading and intensive natural ventilation cooling (SH_{SP} = 100 W/m^2, *ACH* = 3 h^{-1}). In this case, Q_{NH} of the building under the current climate would be 8.4 kWh/m^2, Q_{NC} = 9.1 kWh/m^2, Q_T = 17.5 kWh/m^{2,} and *OV* = 0.21. In terms of its current thermal performance, the building would shift from a heating-dominated to a cooling-dominated building after such energy retrofit.

In general, to achieve high energy efficiency in the considered building, extensive thermal insulation and better insulative windows with relatively high solar radiation transmittance should be applied. The façade and roof colours should remain light, while the occupants should be educated on how to effectively use shading blinds and natural ventilation cooling, such as night ventilation.

Because the projected global warming is expected to decrease Q_{NH} and increase Q_{NC} in the future, any retrofit actions that would be implemented today must also be evaluated for their effect on the increase in Q_{NC}. Therefore, all the retrofit actions were also evaluated according to their overheating vulnerability, i.e., the *OV* score. Table 4 presents the *OV* of the best and the worst 5 percent, i.e., 32 combinations.

As expected, the most overheating resistant (i.e., the lowest $OV = 0.00$) is a retrofit combination including the lowest analysed U_O, U_W, *SHGC*, α_{sol} and SH_{SP}, and the highest *ACH* value (see the range in Table 4). On the other hand, the most vulnerable to overheating ($OV = 1.00$) is the building in its current state.

Table 4. Characteristic parameter values of the best- and the worst-performing 5 percent cases according to the *OV* score.

Parameter	Best 5 % ($OV = 0.00–0.11$)		Worst 5 % ($OV = 0.86–1.00$)	
	mean	range	mean	range
U_O [W/m²K]	0.25	0.20–0.40	1.60	1.60
U_W [W/m²K]	1.14	0.90–1.80	1.34	0.90–1.80
SHGC [-]	0.24	0.20–0.40	0.65	0.65
α_{sol} [-]	0.28	0.20–0.40	0.31	0.20–0.40
SH_{SP} [W/m²]	103	100–200	256	200–300
ACH [h⁻¹]	1.7	0.0–3.0	1.3	0.0–3.0

Observing both groups of the best-performing combinations (Tables 3 and 4), significant discrepancies may only be found in the case of *SHGC*. A higher *SHGC* is recommended to take advantage of solar gains and achieve a lower Q_{NH} and hence Q_T under current climate. At the same time, it represents a higher overheating risk due to higher solar gains during summer. Therefore, the combinations with lower *SHGC* also have lower *OV*.

Based on these observations, Figure 3 shows the energy need for heating and cooling for each case under current climate, while the overheating vulnerability (*OV*) by the end of the 21st century is represented by the circle size. Additional marks show the energy performance of the existing building, the overall four best cases with Q_T below 20 kWh/m² and the two best cases without thermally insulated walls and roof. The latter was singled out because it is the most cost-effective retrofit action, since thermal insulation of the envelope is the most costly analysed retrofit action. In this case, windows should be replaced with those with $U_W = 0.90$ W/m²K and $SHGC = 0.65$, α_{sol} should be between 0.20 and 0.40 (light colours), and effective shading and intensive natural ventilation cooling should be actively used ($SH_{SP} = 100$ W/m², $ACH = 3.0$ h⁻¹).

The results show that the building in its current state is one of the worst performing cases concerning Q_T and has the highest *OV* score. It is evident that any of the analysed energy retrofit actions would be beneficial to improve the thermal performance of the existing building. Therefore, the best retrofit recommendations are presented, and their projected energy needs are discussed in Section 3.3.

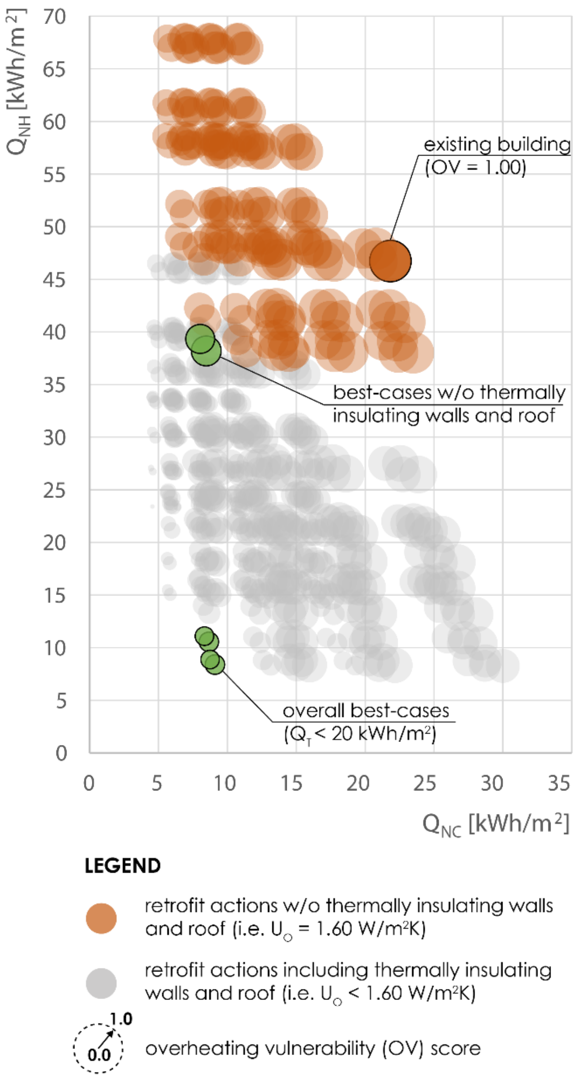

Fig. 3. The energy need for heating (Q_{NH}) and cooling (Q_{NC}) of all 648 models under current climate and their overheating vulnerability (*OV*) score.

3.3 Best retrofit actions

After observing the results in Sections 3.1 and 3.2, the energy retrofit of the analysed multi-apartment building is crucial under the current and future projected warmer climate. Figure 4 shows the projected energy need of the existing building, as well as its projected energy need after applying three characteristic retrofit combinations. Based on the study results, the following three different suggestions for retrofit actions were proposed:

- Best retrofit w/o thermal insulation: $U_O = 1.60$ W/m²K, $U_W = 0.90$ W/m²K, $SHGC = 0.65$, $\alpha_{sol} = 0.40$, $SH_{SP} = 100$ W/m², $ACH = 3$ h⁻¹.
- Most overheating resistant retrofit: $U_O = 0.20$ W/m²K, $U_W = 0.90$ W/m²K, $SHGC = 0.20$, $\alpha_{sol} = 0.20$, $SH_{SP} = 100$ W/m², $ACH = 3$ h⁻¹.
- Overall best retrofit: $U_O = 0.20$ W/m²K, $U_W = 0.90$ W/m²K, $SHGC = 0.65$, $\alpha_{sol} = 0.20$, $SH_S = 100$ W/m², $ACH = 3$ h⁻¹.

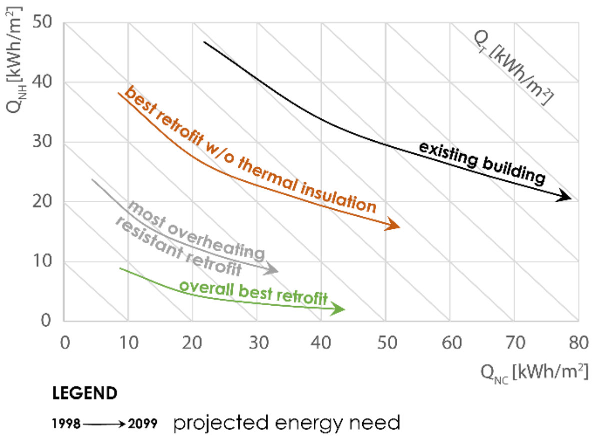

Fig. 4. The projected energy need of the existing building in its current state and three characteristics retrofit combinations.

As can be seen in Figure 4, all the proposed retrofit combinations effectively reduce the energy need of the analysed multi-apartment building in all the studied periods. Therefore, these three retrofit actions were evaluated for their potential effect on electricity and financial savings. The evaluation was based on a case in which the existing building is to undergo energy retrofit in 2022. The potential savings were estimated after 20 and 50 years. The potential electricity savings for heating and cooling (E_{H+C}) were calculated using the air-conditioning (AC) units commonly used for heating and cooling the apartments in the analysed building. The coefficient of performance (COP) for heating was assumed to be 3 and COP for cooling 5. The financial savings were then determined using the average electricity price (i.e., 0.0974 €/kWh) in Montenegro in 2021 [18]. The results are presented in Table 5.

Table 5. Potential savings of three best retrofit scenarios.

Retrofit scenario applied in 2022	**Total savings until 2042**		**Total savings until 2072**	
	E_{H+C} [MWh]	**Funds [k€]**	**E_{H+C} [MWh]**	**Funds [k€]**
Best retrofit w/o thermal insulation	668	65	1733	168
Most overheating resistant retrofit	1253	122	3249	316
Overall best retrofit	1534	149	3778	368

The results presented in Table 5 may be helpful when selecting the appropriate retrofit actions in terms of potential savings and investment cost of specific retrofit actions.

4 Conclusions

The paper discussed the energy retrofit actions and their impact on the overheating vulnerability of the existing multi-apartment building in Montenegro. Overall, the best retrofit actions included comprehensive thermal insulation, better insulative windows with relatively high solar radiation transmittance, light façade and roof colours, effective shading and intensive natural ventilation cooling. Appropriate retrofit can reduce the annual total energy need (Q_T) below 20 kWh/m², representing an approach to the nearly-zero energy building concept in the Montenegrin building stock.

An important conclusion is that occupants should be educated on how to properly use shading and natural ventilation cooling, as these are very effective overheating-prevention actions. However, in the long run, any energy retrofit action should be evaluated in terms of global warming and its long-term savings potential, while cost-effective solutions, such as occupant education, are the most suitable in low-income economies.

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