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ASPECTS REGARDING CLIMATE RESILIENCE AND URBAN HEAT ISLAND EFFECT MITIGATION IN URBAN AREAS RENOVATION PROJECTS

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Abstract

The current context requires the networking of planning decisions on increasing the energy performance of the built environment for sustainability purposes and decisions on reconfiguring urban areas to obtain a resilient environment. The paper aims to highlight ways of multicriterial evaluation on energy performance, environmental performance and resilience in urban areas renovation projects in complementarity with applicable solutions in order to improve the characteristics of the area microclimate. Beyond the aspect of the high energy performance associated with nZEB buildings (Nearly Zero Energy Buildings), we must understand the conditions deriving from the quality of anthropogenic factor that the building has in relation to the urban microclimate, contributing to the amplification of the effect of Urban Thermal Island, a phenomenon with significant impact on the health and quality of life of the inhabitants.

Key words*: climate resilience, local climate zones, nearly Zero Energy Buildings (nZEB), Urban Heat Island (UHI), urban retrofitting.*

INTRODUCTION

The impact of urbanization on the local climate can be analysed through the extent of the urban heat island (UHI) effect. A significant concern is the heightened risk to the population, particularly vulnerable individuals, associated with extreme weather events such as heat waves. The frequency and intensity of these events are increasing in the context of climate change (IPCC, 2022). Cities under the influence of the UHI are experiencing more acute effects with consequences for energy consumption, health and quality of life of residents (Heaviside et al., 2017).

The overheating of urban areas is the cumulative result of several factors that influence the energy balance. These include the high proportion of impervious concrete surfaces, reduced vegetation in densely built-up areas, and anthropogenic heat emissions. It is evident that there is an interaction occurring between the radiative properties of anthropogenic surfaces, reduced evapotranspiration, and changes in ventilation that are attributable to urban morphology (Arnfield, 2003; Grimmond, 2007). This phenomenon is further compounded by anthropogenic heat accumulation resulting from traffic, human activities, and air conditioning, which has the potential to significantly exacerbate local warming (Taha, 1997; Santamouris, 2015b).

Strategies for integrated urban planning have the potential to address climate resilience in densely built-up areas by combining solutions for adapting to extreme heat with those designed to increase energy efficiency and, consequently, environmental sustainability (Constantinescu, 2020). The findings presented support the understanding of the need for convergence between efforts to mitigate the effects of urban heat islands and to increase the adaptive capacity of buildings and urban systems, including green infrastructure and urban morphology, to meet the need for transformative adaptation of cities (European Environment Agency, 2016).

The extant literature highlights mitigation solutions based on the efficiency of cool roof technologies and green roofs (Santamouris, 2014; 2015a), and a comparative quantification of their performance (Li et al., 2014). In addition, the benefits of strategies based on green-blue infrastructure are encompassed, as are the utilization of reflective permeable pavements and quantitative references regarding surface temperature reduction (Li et al., 2022). Furthermore, measures to reduce anthropogenic

heat are also addressed. The classification framework for local climate zones also serves as the morphological basis for urban climate analysis (Stewart & Oke, 2012). However, most studies focus on urban-scale indicators or isolated technical measures rather than an integrated methodological approach.

Although recent studies have paved the way for the simultaneous integration and analysis of the urban microclimate and the energy performance of buildings to area scale assessments (Pisello et al., 2017; Turhan et al., 2023; Skandalos & Karamanis, 2025), these are based on complex simulations or case studies specific to a particular context, with less exploration of assessments aimed at providing framework solutions for the planning of urban area renovations by quantifying the co-benefits of renovation measures with nearly Zero Energy Buildings (nZEB) targets and the reconfiguration of urban surfaces in order to reduce the UHI effect. Furthermore, current local design practice often appears to offer fragmented measures to meet energy and environmental performance requirements, which do not always ensure conditions for resilience at the urban area level (Constantinescu, 2020).

At the level of Bucharest Municipality, studies highlight the high thermal risk associated with heat waves and extreme temperatures faced by a large part of the city's area (Zamfirescu et al., 2025). Despite the demonstrable applicability of UHI analysis based on the assessment of land surface temperature (LST) at the local climate zone level for certain Romanian cities, including Iași (Sfică et al., 2023), integrated scenarios combining nZEB objectives with measures to mitigate the UHI effect remain insufficiently analysed.

The assertion that "*every city will have a heat island*" serves to emphasize the significance of these approaches, as the modelling of the reduction of urban heat island intensity constitutes one of the key objectives in sustainable urban planning projects (Chow & Chugh, 2022). Based on the understanding that quality of life and climate action are complementary goals (Montgomery, 2017) we can expect an improvement in the comfort and health of the population associated with major urban renewal projects that adopt a multi-criteria approach aimed at enhancing energy and environmental performance as well as improving the local climate. It should not be overlooked that the attractiveness of outdoor spaces is closely linked to the improvement of the microclimate; thus, mitigating the UHI effect leads to a lifestyle more in harmony with nature during a period of climate change (Sim, 2022).

Flexibility and adaptability appear to be the key attributes of a soft urban environment that, by integrating density and diversity, can offer residents a more pleasant daily life while also responding, in the long term, to the need for transformative adaptation in a global context (European Environment Agency, 2016).

The present study addresses the issue under discussion by means of an analysis of adaptation solutions. This analysis is based on a comprehensive renovation of multi-family residential buildings exposed to UHI intensity, in accordance with nZEB standards, within a Test Urban Zone that is representative of the city of Bucharest. The purpose of this study is to evaluate the potential of the proposed integrated solution packages to enhance microclimate quality and simultaneously increase energy and environmental performance.

The objective of this research is threefold: firstly, to quantify the current proportion of impervious mineral surfaces characterized by low albedo within the analysed urban area; secondly, to highlight the anthropogenic impact of multi-family residential buildings in their current energy state and the proposed nZEB scenario based on estimates of residual heat emissions into the atmosphere (Marin Lazăr, 2021); and thirdly, to compare integrated intervention scenarios that combine building energy retrofits, the implementation of high-reflectance surfaces, and the expansion of green infrastructure, from the perspective of their potential to reduce the UHI effect and improve climate resilience at the neighbourhood scale. The study's contribution stems from the creation of a unified methodological framework through the simultaneous application of energy and environmental performance modelling, the analysis of intervention possibilities at the level of urban surfaces within identified local climatic zones, and the quantification of anthropogenic heat. The aim of this is to obtain quantitative

indicators that can be used in the development of local climate adaptation strategies.

MATERIALS AND METHODS

The present study proposes expanding the analysis of applicable measures aimed at improving the performance of multi-family residential buildings to meet the nZEB (nearly Zero Energy Buildings) standard. This will be achieved by examining proposals for interventions regarding the proportion and quality of mineral and natural surfaces that can help reduce the UHI effect.
The analysis focuses on a representative test urban area located in Bucharest.

1. Heat Island Intensity in Bucharest _Test Urban Area

The specific exposure indicator for Bucharest regarding UHI intensity is approximately 2.22°C, according to thermal maps generated by processing the climate model available through the Destination Earth (DestinE) project.
The Urban Heat Island Explorer application provides a clear visualisation of the increase in average annual surface temperature under the influence of the UHI effect for European cities.
For the designated Test Urban Area, the UHI effect has been found to cause an increase in this parameter ranging from 0°C to +3°C, with some hotspot areas where the temperature exceeds this threshold (Figure 1).
The area under analysis is located in proximity to the city centre, where temperatures in the air and on the surface tend to be higher. Near the area under study, two major natural features (Lake Fundeni and the National Arena Park) help mitigate the urban heat island effect.

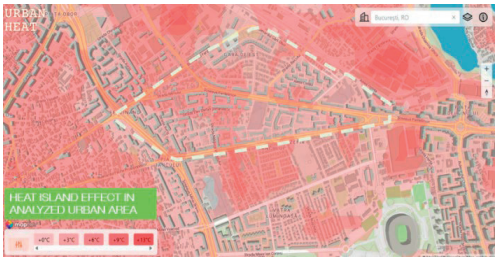


Figure 1. Increase of land surface temperature caused by UHI within the Urban Test Area (https://urbanheat.app/bucuresti)

In order to comprehend the substantial impact of natural spaces in mitigating the UHI effect, it is imperative to acknowledge that surface temperatures in green and aquatic areas remain at 25-28°C, whilst the average surface temperature during the summer months in Bucharest exceeds 35°C and average values for July are above 40°C (Zamfirescu et al., 2025).
The summary Table 1 illustrates climate trends in Bucharest by modelling the increase in average temperatures and the number of tropical nights and days under the RCP 4.5, RCP 8.5 (medium and high impact) scenarios, based on an analysis of measurements taken at the Filaret and Băneasa stations during the reference period 1901-2023 (Zamfirescu et al., 2025).

Table 1. Trends for the projected period 1971-2100, for the RCP 4.5 and RCP 8.5 scenarios, compared with values measured during the period 1901-2023 (Zamfirescu et al., 2025)

Time frame	Scenario	Incrase avg.max. temp. July (°C)	Tropical nights	Tropical days
2041-2060	RCP 4.5	+1.6	10	23
2081-2100	RCP 4.5	+2.2	13	30
2041-2060	RCP 8.5	+1.9	15	29
2081-2100	RCP 8.5	+4.3	46	54

The medium- and long-term projections indicate an increase in vulnerability in the absence of mitigation measures, given the already unfavourable current situation in which over 50% of the capital's population faces a "high or very high risk of extreme temperatures and heat waves" during the summer (Zamfirescu et al., 2025).

2. Analysis of Land Use Types within the Test Urban Area

From a structural, functional and urban planning perspective, the analysed area consists primarily of high-rise apartment buildings (P+8E and P+10E) and is located in Sector 2 of Bucharest, between Iancului Road, Pantelimon Road, Mihai Bravu Road, Obor Station, and Baicului Street. It is also noteworthy that there are several areas with single-family homes located in a secondary position relative to the main traffic arteries (Marin Lazăr, 2021).
From a morphological perspective, the layout of multi-unit residential buildings in the study area can be divided into two subzones, as illustrated

in Figure 2. The first of these is the area near Obor Station, built prior to 1970. This area features a distribution of large-scale residential buildings surrounded by extensive green spaces. The second subzone is developed after 1975/1980 and is characterised by more pronounced densification and a fragmentation of small green spaces situated between the blocks. As demonstrated in the relevant literature, Land Surface Temperature (LST) measurements indicate that this parameter is lower for the first type of building layout and higher for the second situation (Sfică et al., 2023). The analysis of urban areas was conducted, as shown in Table 2, in relation to the two defined subzones, Local Climate Zones LCZ 1 and LCZ 2, based on this observation.

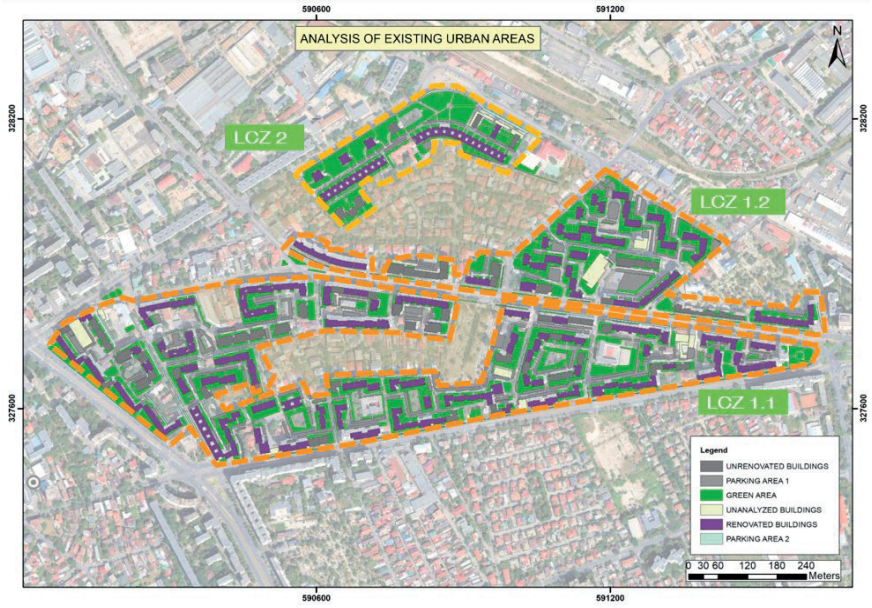


Figure 2. Zonal analysis - indicators of urban composition: built-up/natural areas - existing

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	Total analysed area [m^2]	**Built-up area** [m^2]	**Green space** [m^2]	**Parking area** [m^2]	**Sidewalks, streets, alleys** [m^2]
LCZ 1.1	272,600	77,689	35,626	29,800	129,485
LCZ 1.2	108,036	28,939	16,258	15,955	46,884
TOTAL LCZ 1	**380,650**	**106,630**	**51,884**	**45,755**	**176,369**
LCZ 2	**64,231**	**12,349**	**13,001**	**4,391**	**34,490**

An analysis of urban areas highlights the low proportion of natural spaces, approximately 14.5%, compared to man-made areas, which account for approximately 85.41% of the total analysed.

For subzone LCZ 1, it is noteworthy that green spaces account for only about 50% of the built-up area, or 13.6% of the total subzone, while for subzone LCZ 2, the ratio of built-up area to green space is slightly more favourable to the latter, reaching approximately 20% of the subzone (Figure 3).

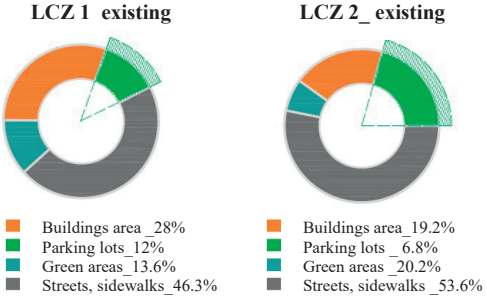


Figure 3. Proportion of anthropogenic existing areas versus natural areas

This mix influences the local energy balance, given that existing man-made surfaces (rooftops of apartment buildings covered with bituminous membranes, courtyards, parking lots, streets, alleys, and sidewalks) are characterised by low albedo and high thermal storage capacity and thus absorb a greater amount of solar radiation during the day, which they gradually release at night, amplifying thermal discomfort (Oke, 1982; Taha, 1997). The high degree of imperviousness of the area as illustrated in Figure 4, and the low percentage of vegetation amplify this effect by limiting evaporative cooling (Arnfield, 2003; Gago et al., 2013).

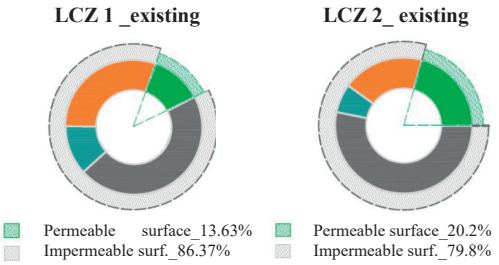


Figure 4. Ratio of permeable/impermeable surfaces (high solar radiation absorption)

3. Energy Performance Analysis - Multi-family Residential Buildings in the Test Urban Area

The present energy status of the Test Urban Area, as determined by the energy and environmental performance of multi-family housing, demonstrates elevated levels of specific primary energy consumption (kWh/m²·year) and associated CO_2 emissions (kg/m²·year), particularly for buildings that have not undergone previous energy renovation programs, accounting for approximately 31% of the total. The numerical results were supported by dynamic modelling of the building envelope response, as presented in detail in the relevant literature (Constantinescu, 2008; 2020).

The mean zonal values of these indicators (across all buildings belonging to both energy typologies, designated CRA and CRR) are 183.74 kWh/m²·year of specific primary energy and 41.98 kg/m²·year of CO_2 emissions (Table 3). These are well above the threshold for classification in the nZEB (nearly zero-energy building) performance category and thus place the area in a lower energy and environmental class (Marin Lazăr, 2021).

Table 3. Assessment of energy consumption in the test urban area - existing (Marin Lazăr, 2021)

Energy TYPE CRA/ CRR	Specific net energy consump. (kWh/m²/ year)	Specific net CO_2 emissions (kg/m²/ year)	Enviro. energy class	Heat emissions (kWh/m²/ year)/ (MWh/year)
Regional Enviro. LCZ1+LCZ2	**183.74**	**41.98**	4 /4	2.42 / **802**
nZEB 2030	43-74	9-19	2/2	
nZEB 2050	< 43	< 9	1/1	

4. Assessment of the anthropogenic impact of multi-unit residential buildings

To assess the anthropogenic impact of multi-unit residential buildings on the amplification of urban heat islands, the heat emissions released into the atmosphere by the operation of split-type air conditioning units were determined, in correlation with the cooling demand and the performance of the equipment. The quantity of heat emissions into the atmosphere, as shown in Table 4, was calculated on the basis of the usable floor area of the air-conditioned apartments, which was determined to be 330,097 m², thus accounting for approximately 50% of the total area analysed, which was 690,562.6 m² (Marin Lazăr, 2021).

Table 4. Significant results for several representative building types in the analysed area (Marin Lazăr, 2021)

Energy TYPE CRA/ CRR	Usable area (m²)/ Heated usable area	Primary en. building (MWh/ year)	Specific net energy (kWh/ m²/year)	Heat emissions (MWh/year) / (kWh/m²/ year)
CRA P+8E	3066/ 1356	**696**	**223.74**	**5.16** /3.8
CRR P+8E	3093 / 1308	**482**	**155.83**	**2.25** /1.72
CRA P+10E	2450 / 946	**554**	**226.12**	**3.73** / 3.94
CRR P+10E	2459/ 782	**389**	**158.19**	**1.3** / 1.66

It is important to emphasize the reciprocal relationship between buildings - viewed as an anthropogenic factor - and the urban micro-climate, since the waste heat released into the atmosphere raises outdoor temperatures in the immediate vicinity of the building, thereby contributing to a further increase in the energy required for cooling. Given the projected rise in temperatures over the medium and long term - which in urban areas is associated with the Urban Heat Island effect - it can be concluded that, in the absence of energy-efficiency improvements and reconfiguration, the energy demand for cooling will increase.

The adaptability of buildings is supported by passive architectural solutions that help minimise the need for sensible cooling and by connections to technical systems that must ensure the operation of HVAC equipment under severe weather conditions (Constantinescu, 2020).

5. Indicators of the current situation

The specific exposure indicator for the extent of the urban heat island (UHI) in the analysed area falls within the range of 0-3°C. However, higher intensities of 5-6°C may occur under weather conditions conducive to heat waves.

Key findings:

- Analysis of urban surfaces highlights conditions favourable to the amplification of the urban heat island effect at the local level due to the high proportion of impermeable mineral surfaces characterized by low albedo.
- Analysis of heat emissions associated with the operation of buildings in their current energy state illustrates their role as an anthropogenic factor contributing to the amplification of the urban heat island effect.

The European Environment Agency proposes a tool for monitoring climate change adaptation policies organised around the risk, response, and outcome framework (Climate-ADAPT, n.d.). From this standpoint, the text presents several aspects relevant to the analysed case study. These include the current risk level, the proposed intervention scenarios in response to climate challenges, and the relevant outcomes for the analysed area. The assessment of the urban test area highlights an increased risk level regarding extreme temperatures and heat waves, exacerbated by the urban heat island effect (Zamfirescu et al., 2025; UAUIM, 2017). The present analysis of the current situation reveals the thermal vulnerability of buildings during heat waves. This phenomenon can be attributed to the inability to guarantee passive survival conditions in the absence of functional technical systems in dwellings characterised by elevated thermal discomfort (Marin Lazăr, 2021).

6. Measures for climate resilience and UHI reduction

In response to the previously delineated risk scenario, a multi-criteria analysis is required of the possibilities for reducing the UHI effect in the Urban Test Area. This analysis should involve a comparison of the existing situation with integrated intervention scenarios at the level of buildings and urban surfaces. The purpose of this comparison is to ensure improved energy and environmental performance and resilience. The proposed specific objectives are twofold: firstly, to mitigate the adverse effects of the high proportion of impermeable mineral surfaces with low albedo, and secondly, to limit heat emissions into the atmosphere by reducing the anthropogenic impact of buildings (Figure 5, Figure 6 and Table 5).

The proposed intervention plan for urban areas includes:

- Converting impermeable parking lots into permeable surfaces with high reflectivity.
- Using cool roof materials for the flat roofs of multi-unit residential buildings, with the integration of photovoltaic panels.
- Targeted interventions to expand green spaces through green roofs and green urban paving. Areas targeted include the flat roofs of schools and kindergartens within the test urban zone, local heating plant buildings, and ground-floor public spaces. Green roof solutions will be analysed with caution, given the difficulty of maintaining them in light of the current summer rainfall deficit specific to the Bucharest area and long-term climate forecasts.
- The installation of green urban paving can bring social benefits by creating community gathering places, so that solutions to improve the microclimate also facilitate resident's "reconnection" with nature.

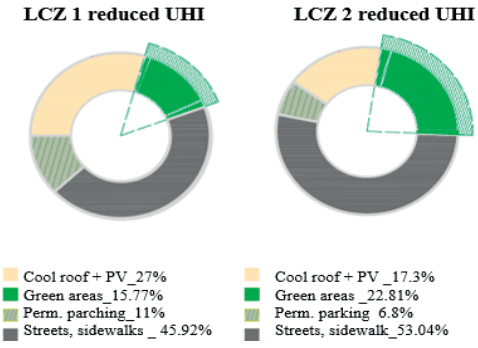


Figure 5. Proposed ratio of anthropogenic versus natural areas

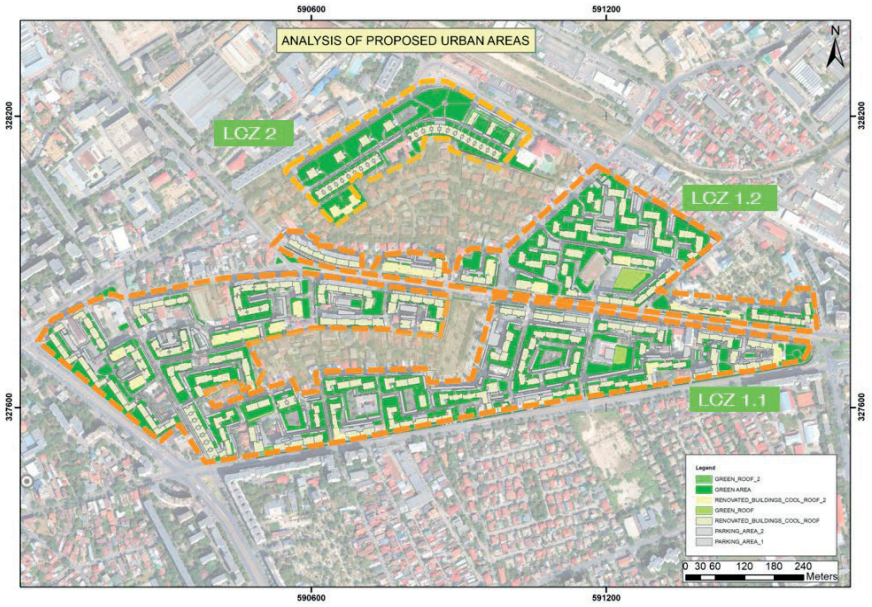


Figure 6. Zonal analysis - indicators of urban composition: built-up/natural areas - proposal

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	Total analysed area [m^2]	Built-up area [m^2]	Green space [m^2]	Parking area [m^2]	Sidewalks, streets, alleys [m^2]
LCZ 1.1	272,600	77,689	40,045	29,800	127,914
LCZ 1.2	108,036	28,939	20,000	13,213	46,884
TOTAL LCZ 1	**380,650**	**106,630**	**60,045**	**43,013**	**174,798**
LCZ 2	**64,231**	**12,349**	**14,652**	**4,391**	**34,072**

The maximum scenario applicable to buildings and the modernization of technical systems includes (Marin Lazăr, 2021).

- Passive solutions for the building envelope are to be implemented in order to ensure an appropriate level of thermal insulation and airtightness, as well as the installation of shading systems. The following solutions are to be put into effect: reflective folding thermal insulation shutters and the use of high-albedo façade finishes and cool roof systems with solar radiation absorption coefficients α abs. Wall = 0.3 / α abs. Terrace= 0.1.
- The technical systems to be implemented in the analysed buildings - heat recovery ventilation systems.
- Modernisation of the district-level heating and electricity supply system – high-efficiency cogeneration/trigeneration, and connection of all buildings within the test urban area.
- Installation of photovoltaic panels to harness the area's potential for renewable energy production. The sizing of the panels will account for the building's calculated sensible cooling demand determined under summer design conditions. We should mention that PV have a theoretical efficiency of 22% in laboratory conditions (low net temperature to the outside). In urban conditions, in hot summer days, the efficiency of solar radiation transformation into electricity is about 12%-15% associated with the high temperature of the PV capture surface, 60-70°C. PV produces electric energy, but also thermal pollution. Prosumers are effective for remote areas or in rural areas.
- To ensure conditions for climate resilience, additional nighttime ventilation systems for the spaces via a perforated false ceiling may be selected. This requires that the outdoor temperature drop below 24°C.

Based on indicators of vulnerability, exposure, and adaptive capacity, key measures have been identified that focus on technological adaptation solutions applicable to buildings and built-up areas, as well as green options.

RESULTS AND DISCUSSIONS

1. Estimated outcome of intervention scenarios for urban areas aimed at reducing the urban heat island effect

The proposed intervention scenario ensures an increase in areas conducive to lower temperatures within the test urban area compared to the current situation. In subzone LCZ 1, the proportion of permeable surfaces will increase, from 13.63% to approximately 27%, and from 20% to 29.6% in subzone LCZ 2 (Figure 7).

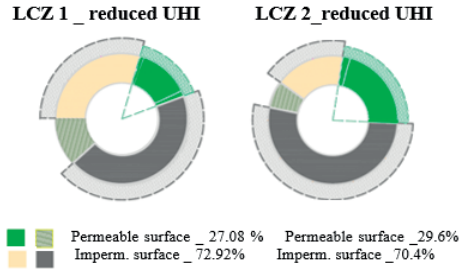


Figure 7. Ratio of permeable / impermeable surfaces

These changes result from the conversion of parking lots from impermeable mineral surfaces to permeable surfaces with high solar reflectance and the cumulative effects of increasing green spaces integrated into the balance of surface categories relative to the analysed area.

Concurrently, the proportion of surfaces with low solar radiation absorption (including cool roofs and the conversion of parking lots) will increase significantly in LCZ 1 from 13.63% to approximately 54.08% and in LCZ 2 from 20.2% to 46.9%. At the same time, the proportion of surfaces with high absorption decreases - 45.92% in LCZ 1 and 53.04% in LCZ 2 - which leads to a reduction in the solar radiation load on the analysed area (Figure 8).

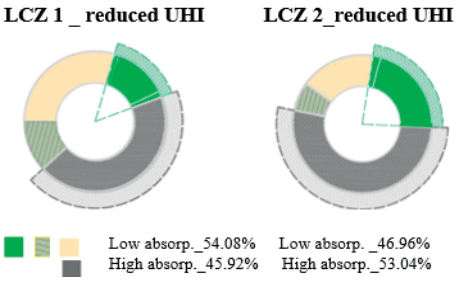


Figure 8. Ratio of high solar radiation absorption

2. Estimated results of building-level intervention scenarios

The energy and environmental impact of the technological adaptation measures was estimated by comparing the existing and proposed scenarios regarding net primary energy (kWh/m² per year) and CO_2 emissions (kg/m² per year) for buildings in their current state and after implementing the renovation solution packages.

Compared to the permissible thresholds for compliance with the nZEB standard by 2050, it is necessary to combine passive architectural solutions applicable to the building envelope with systems for recovering energy from exhaust air, utilizing the regional potential for renewable energy production, as well as connecting to high-efficiency district heating systems of the cogeneration/ trigeneration type. The solutions analysed implicitly lead to a reduction in the amount of waste heat released into the atmosphere, which results in the emission levels shown in the following Table 6.

Table 6. Assessment of energy consumption in the test urban area - proposed (Marin Lazăr, 2021)

Energy TYPE CRA/ CRR	Specific net energy consump. (kWh/m²/ year)	Specific net CO_2 emissions (kg/m²/ year)	Enviro. energy class	Heat emissions (kWh/m²/ year)/ (MWh/year)
Regional Enviro. LCZ1+LCZ2	**22.16**	**4.64**	1/1	0.85 / **283.31**
nZEB 2030	43-74	9-19	2/2	
nZEB 2050	< 43	< 9	1/1	

3. Significance of the Results

In relation to the configuration of urban surfaces, the results of the analysis confirm that, at present, the proportion of impervious surfaces - 86.37% in subzone LCZ1 and 79.8% in subzone LCZ2 - contributes to the amplification of the UHI effect within the test urban area. The reported values are higher than the critical imperviousness threshold of 70%, which leads to a marked decrease in the soil's evaporation and cooling capacity, resulting in an increase in the UHI effect by more than 2°C compared to peri-urban areas (Oke et al., 2017). This highlights the area's high thermal vulnerability, correlated with a specific UHI exposure indicator of 0°C to +3°C according to Urban Heat Island Explorer data.

The contribution of the existing built environment, as an anthropogenic factor that further exacerbates UHI intensity, is highlighted by the quantification of residual heat emissions released into the atmosphere by air conditioning units. The total annual average of these emissions across the area is approximately 802 MWh/year (Table 3), reflecting the current energy status of multi-unit residential buildings. Given the medium- and long-term climate projections (Zamfirescu et al., 2025), it can be estimated that in Bucharest we will see an increase in energy consumption associated with space cooling, which could adversely exacerbate the building-urban microclimate feedback loop in the absence of mitigation solutions.

The mean values for specific primary energy were found to be approximately 183.74 kWh/m²·year, and the mean CO_2 emissions were 41.98 kg/m²·year, based on the current level of energy and environmental performance of the analysed buildings. These values illustrate the inadequacy of the solutions generated by previous renovation procedures, based on isolated interventions, as buildings in their current energy state cannot ensure conditions for passive survival at the residential unit level during heat waves and do not meet nZEB objectives (Marin Lazăr, 2021; Constantinescu, 2020).

4. The inner validation of results against study objectives

In terms of the objective of reconfiguring urban surfaces, the proposed intervention scenario results in a significant increase in permeable surfaces, from 13.63% to approximately 27% for subzone LCZ1, and from 20% to 29.6% for subzone LCZ2. At the same time, there is a significant increase in areas with reduced solar absorption, from 13.63% to approximately 54.08% in LCZ 1 and from 20.2% to 46.9% in LCZ 2. The proposed interventions lead to a reduction in solar radiation absorbed within the area.

The proposed solutions to achieve the nZEB target have been shown to result in a decrease in specific primary energy consumption from 183.74 kWh/m²·year to 22.16 kWh/m²·year and in associated CO_2 emissions from 41.98 kg/m²·year to 4.64 kg/m²·year (Marin Lazăr, 2021). The significantly reduced cooling demand of energy-renovated buildings leads to a substantial reduction in heat emissions into the atmosphere, approximately 65% lower than current levels. This implicitly reduces the anthropogenic impact of buildings, which is a relevant aspect regarding the co-benefits of increasing energy efficiency and mitigating the UHI effect.

The objective of comparatively evaluating integrated scenarios is achieved by simultaneously analysing the impact of interventions on urban land characteristics and measures to improve the energy and environmental performance of buildings. This highlights the cumulative positive effect at the urban area level that justifies the integrated, multi-criteria approach to renovation projects compared to isolated, single-focus interventions.

5. External validation of results compared to similar studies

The potential for reducing surface temperature in the analysed test area through the proposed intervention scenarios is qualitatively confirmed by the existing literature. The available reports indicate a potential reduction in surface temperature of up to 34.3°C by replacing dark roofs with reflective roofs equipped with PV, and approximately 8.3°C by converting parking areas from dark impervious to light/permeable surfaces (Li et al., 2022).

The effectiveness of UHI mitigation measures based on green roof and cool roof technologies is increased when implemented at the neighbourhood scale rather than through isolated interventions at the building level (Li et al., 2014), which confirms the need for the urban-scale approach described in this study.

Reference can also be made to the added value of the proposal to partially implement green roofs and permeable pavements, given that multifunctional green infrastructure contributes both to mitigating the urban heat island effect and to stormwater retention and increased biodiversity (Demuzere et al., 2014), which, particularly in Bucharest, given the lack of rainfall during the summer season, requires careful selection of species and minimization of irrigation needs.

The study's findings align with the conclusions summarized in the reports of the European Environment Agency (2016), which show that

integrated interventions combining measures related to green infrastructure, smart surfaces, and building energy performance yield greater benefits in terms of both thermal comfort and public health.

6. Estimated results of building-level intervention scenarios

The present paper puts forward a proposal for the integration of morphological analysis based on the LCZ classification and the modelling of building energy performance, with a focus on the identification and quantification of anthropogenic heat emissions resulting from building operations. This is to be achieved within a unified methodological framework that provides a replicable decision-making tool for the analysis of urban areas with similar functions and characteristics, located in regions with a continental climate and trends toward rising temperatures and heat waves. The quantitative indicators resulting from the analysis – namely, the proportion of permeable surfaces characterised by high albedo, anthropogenic heat emissions, and specific values for primary energy and CO_2 emissions – can be used to develop local climate adaptation strategies and evaluate results in relation to resilience objectives.

7. Limitations of the study, future directions for research

About the interpretation of the results, it should be noted that the analysis of urban surfaces was based on reference parameters from the relevant literature without in-situ validation through direct measurements of ground surface temperature or air temperature in the analysed area using remote sensing data or sensor networks. The scenario does not include an assessment of the influence of urban morphology on natural ventilation and the spatial distribution of temperatures, nor does it include dynamic modelling of the long-term degradation of material performance in terms of permeability and reflectivity, which would lead to a reduction in the estimated benefits.

Heat and pollutant emissions resulting from road traffic significantly influence the urban heat balance (Taha, 1997). Therefore, in addition to the benefits of passive measures and green solutions implemented at the building and surface levels, the study can be expanded to include an analysis of the mobility component relevant to the multi-criteria analysis of urban areas.

CONCLUSIONS

This study confirms and supports the view that reducing the urban heat island effect (UHI) in major urban renewal projects requires more than one type of intervention and can be effectively integrated with building energy performance objectives.

Attempts to recalibrate the area's energy systems so that they meet the performance standards for nZEBs by 2050 contribute to reducing heat emissions into the atmosphere and lessen the anthropogenic impact of buildings (Marin Lazăr, 2021). These two courses of action - the reconfiguration of urban areas and energy-efficient renovation - become interdependent, generating clear climate co-benefits.

Individual measures have limited effectiveness in dense urban areas; tangible results are achieved through the implementation of integrated solution packages that combine green infrastructure, cool surfaces, building solar control, and the reduction of anthropogenic heat (Santamouris, 2015b; Li et al., 2014). The package of solutions proposed following the morphological analysis - by comparing scenarios with the current situation - is based on increasing zonal permeability and albedo, through cool roofs equipped with photovoltaic panels, the conversion of parking lots, as well as targeted interventions to increase green spaces, and has real potential to reduce the UHI effect within the test urban area.

The integrated solutions analysed can serve as a methodological framework for local adaptation strategies aimed at climate resilience, provide quantitative indicators, and highlight the need for integration between public spaces, building performance, and energy infrastructure. The methodological framework, based on the LCZ classification, comparative analysis of scenarios for interventions in urban areas, and integrated energy performance modelling, provides a decision-making tool for climate resilience objectives, replicable for the multi-criteria analysis of renovation projects in similar urban areas.

From the residents' perspective, integrating green infrastructure and public spaces not only provides environmental benefits, but also enhances the appeal of outdoor areas and fosters a reconnection with nature. This approach can also help to improve social cohesion at the urban/neighbourhood level.

This integrated approach, which is based on the understanding that urban climate resilience is a systemic objective, leads to a tangible reduction in the urban heat island (UHI) effect during heatwaves. This contributes to increased urban comfort and climate adaptation, reduced energy consumption and improved quality of life in urban areas.

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