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Decreasing the energy demand in public buildings using nature-based solutions: case studies from Novi Sad (Republic of Serbia) and Osijek (Republic of Croatia)

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Abstract

Background Nature-based solutions (NBS) in urban areas offer an opportunity to improve environmental conditions and to reduce CO_2 emissions towards establishing climate-neutral cities in the next few decades. Furthermore, the implementation of NBSs—vertical or horizontal green infrastructures on public facilities—could in particular improve both climate, including outdoor thermal conditions on a micro-scale (especially during the summer season) and the energy demand of buildings as well as save heating energy during the winter period.

Results On both selected buildings, extensive green roofs were implemented as an NBS intervention. The analysed data were obtained using the monitoring systems (from 2019 to 2022) installed on two public buildings in Novi Sad (Republic of Serbia) and Osijek (Republic of Croatia), with a focus on climate/bioclimate characteristics and thermal transmission capacities. Four automatic weather stations (AWS) were used for microclimate monitoring, along with the heat flow meter (HFM) method, to measure the alterations in the thermal transmittance (*U* value) of a flat concrete roof before and after energy refurbishment and the installation of a green roof. The outcomes of this study show that the air temperatures (*Ta*) and globe temperatures (*Tg*) near the green roof are lower by 0–3 °C for *Ta* and by 0–16.5 °C for *Tg* than the values captured by the AWSs at other locations. An even more interesting fact is that the green roof has a constant cooling potential during tropical nights, and based upon this research, the cooling value is around 2 °C for *Tg* (the *Ta* value is not distinct). The thermal transmittance results show that more savings can be achieved by applying a green roof with an 8 cm thick substrate: *U* values decreased by 50–69%, as measured by two different heat flux sensors.

Conclusions Nature-based solutions, such as the implementation of an extensive green roof, have positive effects on diverse aspects of urban environments and building energy savings, which are particularly evident in extreme seasons, both summer and winter. Applying the proposed monitoring and assessment system could help local communities in their efforts to reduce carbon-based emissions. This paper provides a good example of the implementation of NBSs on a local- and a micro-scale.

Keywords Energy efficiency, Public buildings, Nature-based solutions, Green roof, Thermal transmittance, Cities

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Background

Current and previous events in the modern world, such as the recent COVID-19 pandemic, had a significant socioeconomic impact within the European Union (EU) [1]. Unfortunately, the pandemic was not the only event in past years that caused a shift in our lives—with an increased dependence of energy, and after the outbreak of the "Ukraine war", the EU has got another battle to fight [2]. While wars, embargoes, sanctions and other geopolitical hostilities can disrupt fossil fuel supplies, renewable energy costs are now resilient to such events, unlike those of fossil fuels [3]. As the atmosphere continues to warm every year, resulting in climate change, the European Commission invests 30% of the budget in climate-related programmes, projects, and initiatives [4]. The principles and policies of sustainable development have been recognized since the 1970s. While the focus on sustainable development offers real opportunities to developed countries, developing countries, facing many problems, are generally more oriented toward economic development, which is not always aligned with sustainability principles [5]. The green transition, transition toward economically sustainable growth and economy, which is based on low-carbon solutions, is unfortunately a long-term process [6]. The EU has proposed The European Green Deal, a plan to decarbonise its economy by 2050 and fight climate change, but some Members States remain sceptical of this policy [7, 8].

While working hard to reduce fossil fuel consumption and make the environment more desirable to live in, the EU tends to fight against one of the legacies of previous times with an equal passion, making the reduction of energy demand in buildings through the adoption of energy efficiency policies one its key pillars [9]. Studies demonstrate that European residential buildings account for up to 40% of energy consumption and up to 36% of CO_2 emissions [10], offering solutions regarding the prioritisation of energy efficiency intervention in such buildings [11]. Energy efficiency in public buildings is not a problem limited to the EU. It is widespread all over the world. The UN Sustainable Development Goals (Agenda 2030) prove that the problem is global [12].

According to Eurostat, the gross primary energy consumption in the Republic of Croatia in 2021 was 9.61 Terawatt hours (TWh) and the final energy consumption was 8.1 TWh [13]. For the Republic of Croatia over the past 15 years, the balance in primary energy supply of oil and oil products accounted for 50%, while the share of natural gas was 25.6% [4]; renewable energy sources accounted for 31.33% of Croatia's energy mix, with 53.47% of the total electricity production coming from renewables, primarily large hydropower plants [3]. The Republic of Croatia imports about 54.54% of the total energy consumed annually [13]: 74.48% of natural gas, 78.34% of oil and petroleum products, and 100% of its solid fossil fuel needs. The Republic of Croatia also co-owns the Krško nuclear plant in Slovenia, which is included in its energy mix as imported electricity [13]. In 2020, the Croatian government adopted a new Energy Strategy until 2030, with an outlook through 2050 [14]. The Strategy tends to improve energy independence, to increase energy efficiency, reduce dependence on non-renewable sources, and increase production from renewable resources. The Strategy predicts that renewable energy resources as a share of the total energy consumption will grow to 36.4% in 2030 and to 65.6% in 2050. Buildings are complex energy systems and the largest individual energy consumers; the European buildings sector is responsible for about 40% of the total primary energy consumption [15, 16]. Furthermore, the stock of residential buildings constructed before the 1970s, which have a low performance regarding energy saving, makes up for more than three-fourths of the total existing residential buildings in the European Union [17]. The situation is the same in the Republic of Croatia, where approximately 70% of the total existing buildings are constructed before 1980 [18]. The Croatian national nZEB plan was adopted in 2015. The minimum threshold for the primary energy ranges between 50 kWh/m2a and 80 kWh/m2a; the final heating demands is 50–75 kWh/m2a and the final cooling demand in residential buildings is 25–60 kWh/m2a [19]. Renewable energy sources must cover at least 30% of the annual site energy [19].

According to the Statistical Office of the Republic of Serbia [20], the gross primary energy consumption in 2021 was: 0.013516 TWh solar photovoltaic, 1.084541 TWh wind energy, 11.984227 TWh hydroenergy and 0.650913 TWh electricity. The overall energy production by transformation was 38.235523 TWh (0.013516 TWh solar photovoltaic, 1.084541 TWh wind turbines, 11.984227 TWh hydroenergy, 23.733678 TWh thermal power plants and 1.419561 TWh other types of energy production) [20]. According to the International Renewable Energy Agency (IRENA), the overall energy import amounted to 229 476 TJ (Terra Joules) in 2015 and 256 531 TJ in 2020—37% and 39% of the supply, respectively [21]. Unfortunately, the overall growth of the Total Energy Supply (TES) for non-renewable energy was 531,780 TJ in 2015 and 553,035 TJ in 2020, while the TES for renewable energy was only 82,681 TJ in 2015 and 112,804 TJ in 2020. Although there is a small increase in renewable energy production between 2015 and 2020, it is still insignificant compared to the non-renewable production growth [21]. In 2015, the Republic of Serbia submitted the Intended National Determined Contribution (INDC) to the United Nations Framework for the Convention on

Climate Change (UNFCCC), while in 2022, the second National Determined Contribution (NDC) was submitted. It puts forward the intention to reduce greenhouse gas (GHG) emissions by 2030—by 13.2% compared to the 2010 level and by 33.3% compared to the 1990 level [22]. According to the Long-Term Strategy for Encouraging Investment in the Renovation of the National Building Stock of the Republic of Serbia by 2050, residential and non-residential buildings, both public and private, will be provided with financial support to improve energy performance and ensure energy modernisation [22].

Nature-based solutions (NBSs) should play a crucial role in decreasing the energy demand of buildings, decarbonising cities, fostering urban biodiversity, improving biometeorology conditions, and helping achieve a higher quality of well-being for the urban population [23, 24]. To support natural processes in cities, NBS interventions, as an act of intervening in existing ecosystems by applying various techniques, should be enforced [24]. Therefore, NBSs can provide effective solutions for: the cooling of 'hot spots' in cities; the regulation of outdoor and indoor thermal conditions during hot days and tropical nights; the reduction of greenhouse gases and pollutants (particularly CO_2 and PM2.5 particles); the improvement of the energy efficiency of public and private facilities and of the public health, particularly in terms of reducing cardio and respiratory diseases. Generally speaking, NBS can be part of sustainable approaches and ecosystem services in cities [23, 25–29].

As stated in the Research and Innovation concept [30], by working with nature, rather than against it, communities can develop and implement solutions that pave the way towards a resilient, resource-efficient and green economy. Since the direct carbon emissions of buildings account for a significant proportion of total carbon emissions, while energy efficiency investment incentives through building materials have weakened, NBSs have emerged as an alternative approach for reducing building energy demands [31]. Several projects have presented green façade solutions that not only contribute to the energy efficiency of the buildings, but also improve their thermal comfort and aesthetic appeal [32]. NBSs applied in building industry have the potential to be cost-efficient, i.e. they can yield good results without huge costs, and resource-efficient using building materials, natural resources and energy in a sustainable way, while minimizing impacts on the environment [33].

Studies show that NBS interventions and expected contributions from the NBS infrastructure are in accordance with the European Green Deal [34] and the New European Bauhaus [35] concepts, with the overarching goal of making Europe climate-neutral by 2050. These concepts foster the transformation of economy and society towards sustainable development by creating a revolution in green industry (4.5 million green jobs in the European economy were opened from 2001 to 2019); rising the ratio of clean energy systems that produce renewable energy (by 2030 the target is 42.5% of new renewable energy); renovating buildings for greener lifestyles with the goal to improve the energy performance of buildings across Europe; working with nature to provide a high level of public health and to capture more greenhouse gases.

According to the CORDIS database, created by the European Commission, there are more than 2,000 projects (finished or ongoing) dealing with the topics related to urban biodiversity, renewable energy, decarbonization of cities, greening of cities, urban climate and bioclimate, and similar urban environment issues. The projects that stand out by activities and proposed solutions related to NBS and the urban environments include: (a) ThinkNature—with the main goal to develop a multi-stakeholder communication platform that provides support and ensures the promotion of NBS at the local, regional and international levels; (b) Nature4Cities, which develops complementary and interactive modules (the N4C platform) for engaging stakeholders in the process of collective education on urban greening, the development and circulation of new businesses, financial and management models for nature-based projects; (c) UNaLaB, which seeks to establish the so-called "Living Laboratories" in cooperation with stakeholders and implement demonstration areas, develop a comprehensive base of examples and a European framework of innovative, replicable and locally oriented NBSs to improve the resilience of cities to climate and hydrological change; (d) URBAN GreenUP, which aims to establish an adaptable methodology that will support the development of urban greening plans focused on climate change adaptation and efficient water management; and (e) CONNECTING Nature, seeking to position Europe as a leader in the innovation and implementation of NBSs [23, 36]. Another project funded by the EU, which is the topic of this study, is GReENERGY, tasked with fostering the implementation of NBSs in public facilities. The main goals of the project are: (a) to encourage the production and use of renewable energy while reducing energy consumption from the conventional sources that are the major emitters of CO_2 and (b) to emphasize the installation of green roofs and green walls on public buildings as one of the NBSs that ensure additional energy efficiency, to help preserve the urban ecosystem by improving the outdoor thermal comfort conditions on a micro-scale. GReENERGY project activities were focused on the implementation of green roofs (total area of 640 m^2) and a green wall (total area of 80 m^2), and the production of 213 kW of additional renewable energy through solar power plants installed on both selected buildings in Novi Sad and Osijek [37]. The entire infrastructure provided through the GReENERGY project will remain the property of respective institutions after the project officially ends. As far as future maintenance after that period is concerned, each institution will be responsible for its own NBS/monitoring implementation.

The research presented in this study was focused on the multifunctional importance and positive impacts of NBSs towards making cities carbon–neutral and climate optimal. Therefore, the main goal was to monitor the positive impacts of NBSs and answer the following research questions: SQ1—to what extent implementing an extensive green roof (in Novi Sad, Republic of Serbia) on public buildings can contribute to the mitigation of outdoor thermal discomfort, especially on days with extremely high temperatures, as well as during tropical nights?; SQ2—to what extent green infrastructure placed on public buildings (extensive green roof in Osijek, Republic of Croatia) can contribute to the reduction of heating energy consumption in buildings during the heating season, helping cities become carbon–neutral in the future?

Methods

Research locations

Osijek is the fourth largest city in the Republic of Croatia, with 60 km^2 of built-up and urban green/blue areas and a population of 97,000 people (data from 2021). The city is located in the Pannonian Plain between the Drava and Danube rivers in Central Europe (45° 33′ N, 18° 41′ E). The average absolute elevation of the city is 94 m (Fig. 1A). According to the Köppen–Geiger climate classification system [38], Osijek has a Cfb climate (temperate climate, fully humid, warm summers, with at least 4 months of the average air temperature above 10 °C). The mean monthly air temperature ranges from −0.2 °C in January to 21.3 °C in July, and the mean annual precipitation is 655 mm (based on data between 1971 and 2000) [39].

The selected public object in Osijek was the Sports and Recreational Complex of the High School Playground (Fig. 1B). Through the GReENERGY project, an extensive green roof with an area of 160 m^2 and a solar power plant with the power of 93 kW were installed on this facility. The building was erected in 1964, with a gross area of 1045.65 m^2 and a usable area of 878.85 m^2. The Sports and Recreational Complex of the High School Playground consists of two heated floors—the ground floor and the first floor. The building uses remote heating with a boiler room connected to the city’s hot water system. The facility is locally supplied with hot water from electric boilers. The building does not have air conditioning, mechanical ventilation and cooling systems. Cooling devices (split system) have been installed for the local cooling of individual rooms. In general, the facility’s energy consumption was high. Using funds provided by the GReENERGY project, the insulation was reconstructed in the whole building [40].

Novi Sad is the second largest city in the Republic of Serbia, with 102 km^2 of built-up and urban green/blue areas and a population of 325,000 [41]. The city is located near the Danube River in the Pannonian Plain in Central Europe (45° 16′ N, 19° 50′ E); accordingly, the most of the urban area is flat with an absolute elevation between 72 and 80 m [42] (Fig. 1C). Novi Sad has a Cfb climate according to the Köppen–Geiger climate classification system [38]. The mean monthly air temperature ranges from −0.3 °C in January to 21.8 °C in July, and the mean annual precipitation is 623 mm (based on data between 1949 and 2015) [43].

The selected public facility in Novi Sad was the School for Primary and Secondary Education (SPSE) "Milan Petrović" (Fig. 1D). On this building, the NBS was implemented by installing an extensive green roof with an area of 480 m^2 above the physical training hall, a small green wall with an area of 80 m^2, and a solar power plant with the power of 120 kW on the roof of the school. The SPSE "Milan Petrović" school is the largest building in Novi Sad housing an education institution. It was built in 2010 as a detached building on a rectangular plot with a total area of 11,538 m^2. The gross area of the building is 7244.64 m^2, while the net area is 6034.15 m^2; where the ground floor area is 4175 m^2, and the total heating area is 5719 m^2. The size of the building and its multiple purposes required complex construction solutions, and it was divided into several parts, with different purposes and functionalities and thus with different thermal zones [40, 42].

Monitoring methodologies and data sets

Monitoring thermal micro-scale conditions around a facility in Novi Sad

As one of the GReENERGY project outcomes, four static Davis Vantage Pro2 automatic weather stations (AWS) equipped with Globe sensors, were deployed around the SPSE "Milan Petrović" building in Novi Sad (Republic of Serbia). This AWS network was used for the comprehensive monitoring of climate and outdoor thermal comfort conditions on a micro-scale. The criteria for the selection of sites included their suitability for data acquisition and the availability of electricity and security requirements. All stations were mounted on building walls of different heights (Fig. 2). Each station was equipped with a Davis Vantage Pro2 sensor set, sensors for measuring air temperature, air humidity, wind speed and direction and

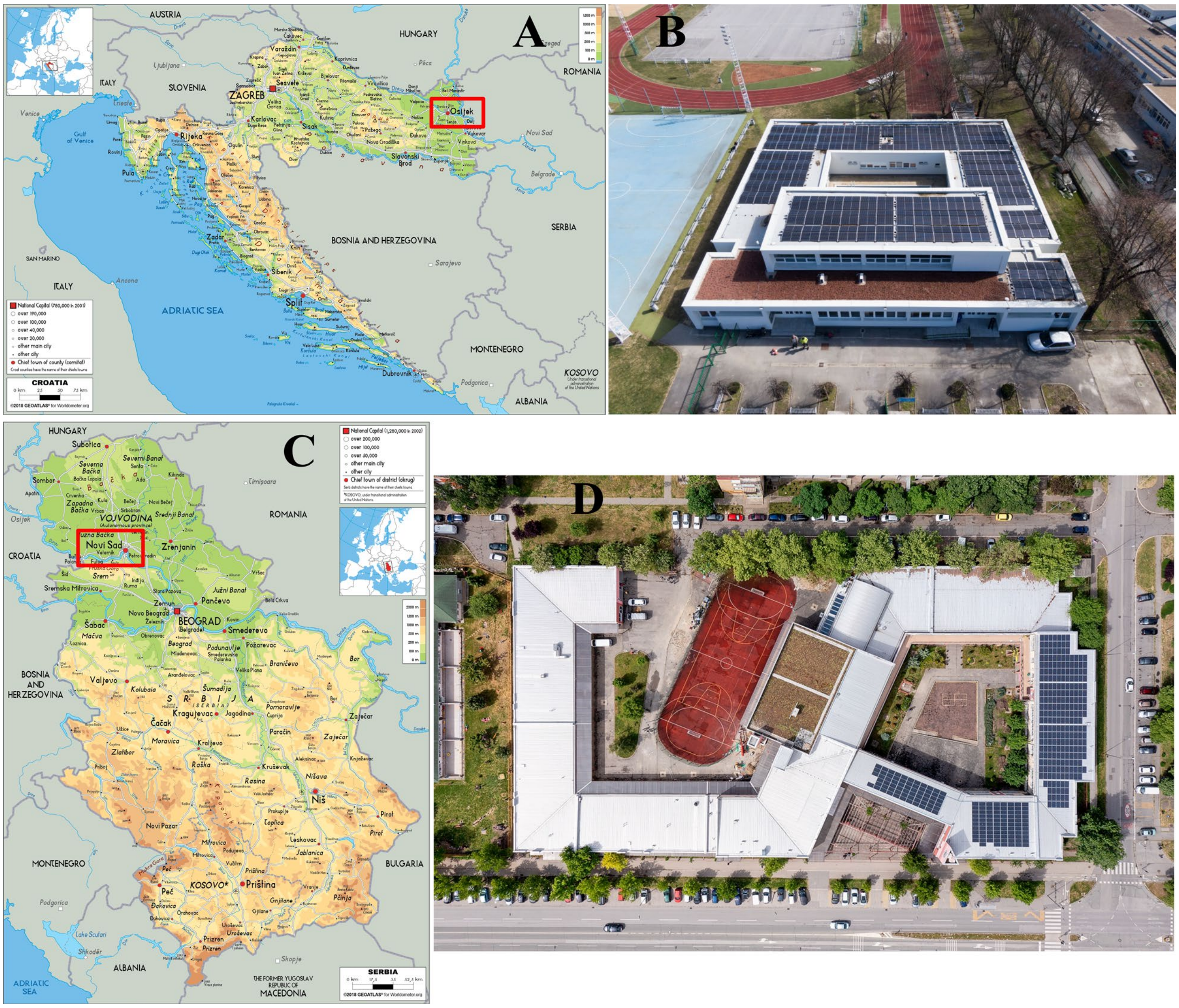

Fig. 1 **A** Geographical location of Osijek in the Republic of Croatia and Europe. https://www.worldometers.info/img/maps/croatia_physical_map.gif; **B** Sports and Recreational Complex of the High School Playground with the implementation of a green roof (160 m^2) and a solar power plant (93 kW); **C** geographical location of Novi Sad in the Republic of Serbia and Europe; Source: https://www.worldometers.info/img/maps/serbia_physical_map.gif; **D** SPSE "Milan Petrović" with the implementation of a green roof (480 m^2) and a solar power plant (120 kW) Source:

solar radiation, and with a Testo Globe sensor. The *Tg* is referred to as the globe temperature or black globe temperature and it resembles the thermal values of the environment, simulating the thermal conditions felt by the human body [44]. AWSs measure new data every 10 min and each measurement time is recorded as UTC. Based on previous research [45–47], the 10-min interval used for measuring of the environmental variables proved to be sufficiently frequent for climate and bioclimate analysis.

This study is based on the analysis of a 10-min interval data set from all four AWS: 301—roof/street side; 302—schoolyard/solar panels; 303—green roof; and 304—schoolyard/garages (Fig. 2). Furthermore, the research period covered the year 2022, with the focus on heatwaves and "hot day" conditions during the summer season. “Heatwave” is defined as a period with a minimum of three consecutive days with maximum air temperatures higher by 5 °C or more than the average temperature for a particular period of the year. According to the generally accepted definition, "hot day" is a day when the maximum air temperature is at least 30 °C [48]. This "hot day" threshold is representative of the climate conditions in Germany and can, therefore, be considered as representative of Central Europe and a part of Southeast Europe, which have similar climate characteristics.

Fig. 2 Locations of the AWSs installed around the SPSE "Milan Petrović" building in Novi Sad (Republic of Serbia)

Finally, for spatial and temporal thermal assessments, the air temperature (*Ta*) data set was used together with the globe temperature (*Tg*) data sets.

Monitoring the thermal transmittance of the facility in Osijek

This research used the heat flow meter (HFM) method to measure the *U* value of a flat concrete roof before the energy refurbishment of the building, after the application of a thermal insulation layer on the roof and finally, the *U* value of the green roof measurement. This method is a non-destructive, standardized procedure, often used to estimate the thermal transmission properties of plane building components. It is based on creating a minimal temperature gradient between the indoor and outdoor temperatures to guarantee adequate heat transfer. It is particularly useful for flat building elements with opaque layers that are perpendicular to the heat flow and do not have significant lateral heat transfer [49]. The first ISO 9869 standard providing the guidelines for the HFM in situ measurement of thermal transmittance and thermal resistance was introduced back in 1994 and, subsequently, in 2014 it was technically revised according to ISO 9869-1:2014 [49]. The ISO 9869-1:2014 standard outlines that the procedure for measuring thermal transmittance involves the direct measuring of heat flow rate and temperatures on both sides of the building element under steady-state conditions. To obtain the *U* value of the tested element, at least one heat flow meter should be positioned on the surface of the element that is in contact with a more stable temperature, in addition to two ambient temperature sensors. According to ISO 9869-1:2014 [49], it is necessary to conduct measurements for at least 3 days to estimate the *U* value of the element if the temperature around the HFM is stable. If the measurement cannot be completed within 7 days, the time interval should be extended accordingly.

Figure 3A shows the layout of measurement devices placed in the building during the measurement process. The position of the heat flux sensor was determined using infrared thermography, which helped avoid errors

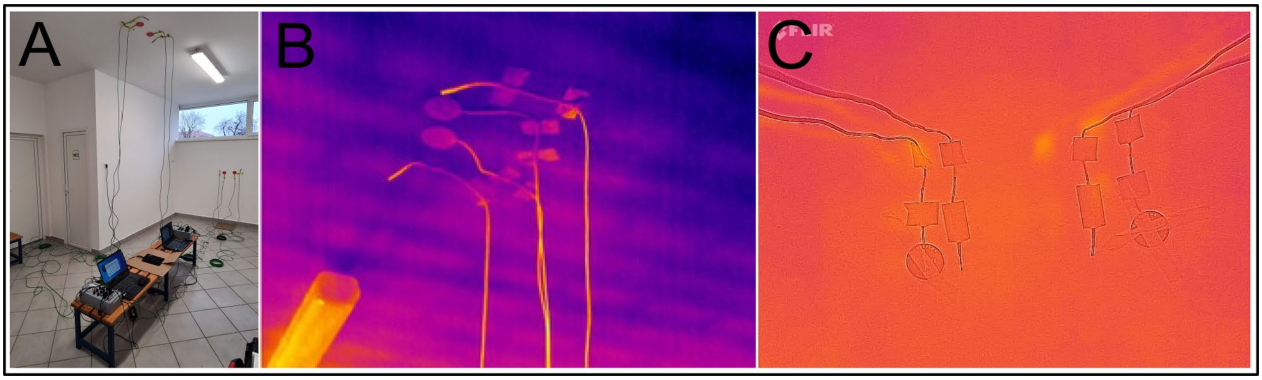

Fig. 3 **A** Layout of measurement devices during measurements; **B** positioning the heat flow metres on the surface of the element using infrared thermography, before; **C** and after energy refurbishment

resulting from thermal bridges, cracks, construction joints and other similar factors of the roof, Fig. 3B and C. According to Albatici et al. [50], site-related factors that can affect thermal performance include weather conditions before and during the test, such as wind speed, solar radiation, precipitation, and humidity, particularly in relation to the site's typical climate. Building-related factors, such as the aging of materials and proper installation during construction, have a significant impact. Lastly, the operating conditions, such as building user management and maintenance work, are considered the most influential factors. In general, the level of agreement between measured and calculated U values varies considerably and the degree of discrepancy depends very much on the type of the examined structure [51]. In this research, the calculated U values are not presented since the research goal was to determine the in situ difference of the U values for different conditions of the flat roof and to determine the contribution of the green roof installation to the reduction of U values. According to the ISO 9869-1:2014 standard, the uncertainty of in situ measurements performed by HFM ranges from 14% to 28% [49].

Throughout the measurement process, data must be recorded continuously at predetermined intervals. In this research, a 10-min interval was applied. To obtain accurate measurements, the impact of heating/cooling systems, rain, snow, and solar radiation was minimized in the following way: (a) the first measurements lasted for 13 days (further labelled as Measurement *M1*) for the concrete flat roof before the energy refurbishment of the building (Fig. 4A); (b) the second measurement (Measurement *M2*) lasted for 23 days after the application of thermal insulation (20 cm of mineral wool) (Fig. 4B); and (c) the third measurement (Measurement *M3*) lasted for 13 days after the green roof installation (added 8 cm of substrate at the top of the building) (Fig. 4C). The three measurement campaigns were performed between December 2019 and February 2023.

Results

The assessment of thermal outdoor conditions on a micro-scale

The AWSs around the school building in Novi Sad were in function from 2021, but during the monitoring time, there were different technical and software issues due to which a certain amount of data was missing. Therefore, to provide relevant thermal assessments, a shorter research period was used in this study and it was limited

Fig. 4 **A** Concrete flat roof before energy refurbishment; **B** construction work in progress during the application of thermal insulation on the flat roof; **C** green roof after the completion of energy refurbishment

to the data sets from the summer season when hot days were detected. The overall effect of the assessment can be explained logically because the goal of the research is to present possible effects of NBSs during hot thermal events—in this case during periods/days with very high air temperatures.

Table 1 presents very small differences in *Ta* values between AWSs during both selected heatwaves in the summer of 2022. In general, the lowest values appeared at AWS 303, and compared to other AWSs, the differences ranged from 0.0 °C (June/Max, July/Average) to 1.5 °C (July/Max—303/302), particularly for *Average* and *Max values*. The situation is clearer for *Tg* values, where in all cases, the temperatures from AWS 303 were lower than those collected at other stations, and the most notable differences were for *Average* and *Min values*. *Tg* differences reach up to 3.3 °C (July/Min—303/302) and only in one case the lowest *Tg* value appeared at AWS 304 (July/Max) (Table 1).

Table 2 presents *Ta* and *Tg* differences between AWSs on the hottest day (July 23rd) during the heatwave period in July 2022. Thermal assessments were done for daytime (9.00–17.00 UTC) and night-time (19.00–5.00 UTC), respectively. Again, *Ta* differences were in both cases (daytime and night-time) quite small—in most cases less than 1 °C, and the minimum values were captured at AWSs 303 or 304. In the case of *Tg* values, differences were more prominent, particularly during night-time. During daytime, the lowest *Tg* values were captured at AWS 304, and the highest values came from AWS 302. The highest value for *Minindex* came from AWS 303 (44.8 °C). During night-time, the lowest *Tg* values in all cases were captured at AWS 303 and differences ranged from 2 °C (Min 303/304) to 3.8 °C (Max 303/302) (Table 2).

Figures 5 and 6 graphically present *Ta* and *Tg* changes during daytime (Fig. 5) and night-time (Fig. 6) on July 23rd 2022. According to Fig. 5A, *Ta* values at AWS 303 were constantly lower than those at AWSs 301 and 302 between 9.00 UTC and 15.00 UTC, and these differences reached almost up to 3 °C. After 15.00 UTC, the *Ta* values were higher at AWS 303 than at AWS 302, and the difference reached up to 1 °C. The situation was different as regards the values obtained at AWS 303 and AWS

Table 1 General thermal characteristics of the air temperature (*Ta*) and globe temperature (*Tg*) from AWSs during the selected heatwave periods in the summer of 2022

	Ta				***Tg***			
	301	**302**	**303**	**304**	**301**	**302**	**303**	**304**
Heatwave: June 27th–July 1st 2022								
Average	29.6	–	29.4	29.7	–	–	35.8	37.6
Max	37.8	–	37.8	37.8	–	–	58.3	59.0
Min	20.0	–	20.6	20.6	–	–	19.0	21.0
Heatwave: July 21st–26th 2022								
Average	29.5	29.8	28.7	28.7	–	39.9	34.2	35.6
Max	40.6	41.1	39.4	38.9	–	63.3	59.3	57.3
Min	20.0	20.0	20.0	20.0	–	21.8	18.5	20.3

Table 2 General thermal characteristics of the air temperature (*Ta*) and globe temperature (*Tg*) in the hottest daytime and night-time periods (hot day) during the heatwave in July 2022

	Ta				***Tg***			
	301	**302**	**303**	**304**	**301**	**302**	**303**	**304**
July 23rd 2022—daytime from 9:00 to 17:00 UTC (from 11:00 to 19:00 CEST, local time)								
Average	38.9	39.0	38.1	37.8	–	56.0	53.8	50.4
Max	40.6	41.1	39.4	38.9	–	63.3	58.3	56.3
Min	36.7	36.7	36.1	35.6	–	39.3	44.8	39.3
July 23rd/24th 2022—night-time from 19:00 to 5:00 UTC (from 21:00 to 7:00 CEST, local time)								
Average	26.5	26.8	26.5	26.4	–	29.6	26.1	28.0
Max	31.7	31.7	31.7	31.1	–	35.3	31.5	34.0
Min	23.9	23.9	23.9	23.9	–	26.0	23.0	25.0

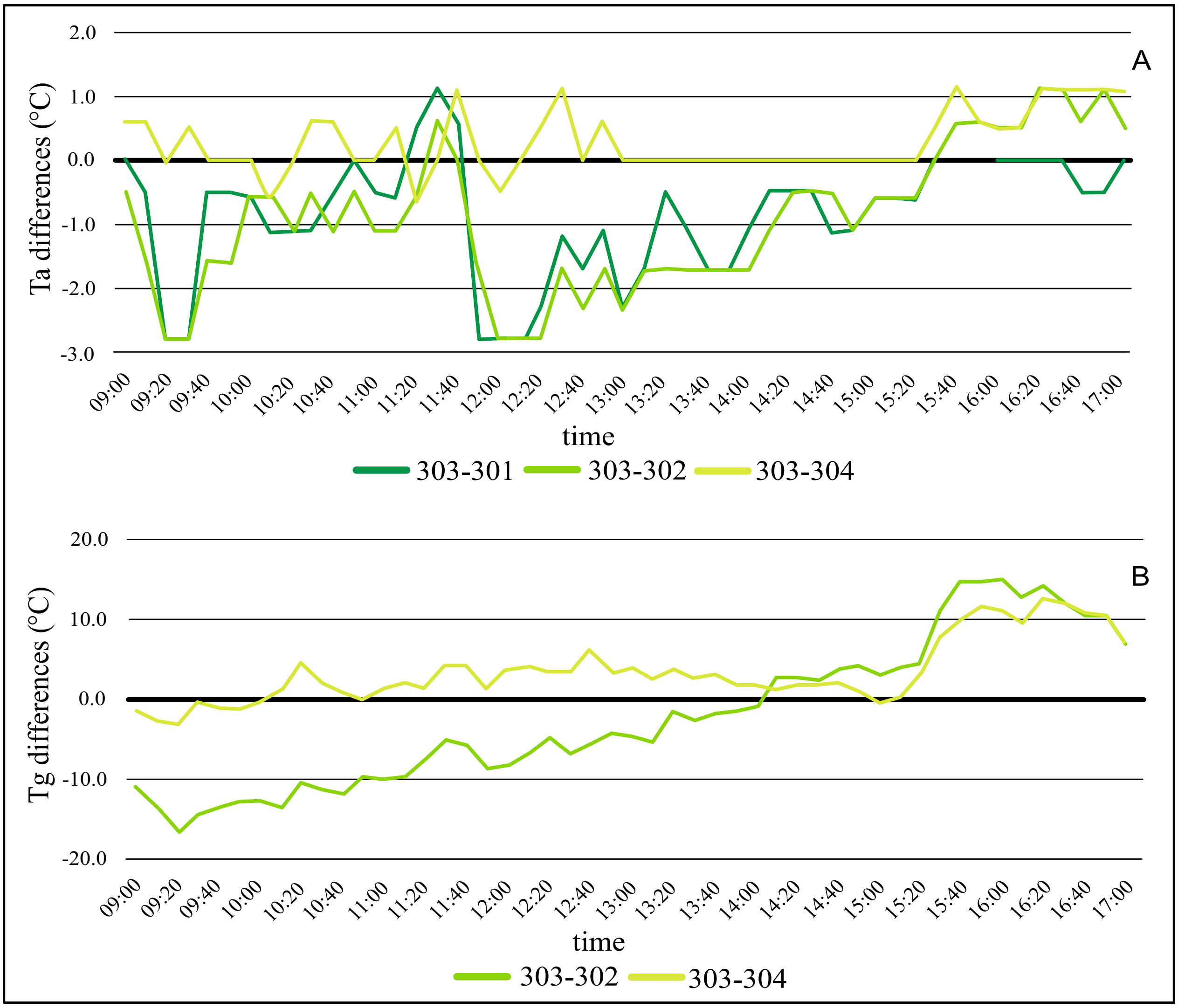

Fig. 5 Thermal differences (in °C) between AWSs during the hottest daytime (July 23rd, from 9:00 to 17:00 UTC) during the heatwave in July 2022, **A** *Ta* differences; **B** *Tg* differences

304, where *Ta* differences were around 0 °C, and in a few cases, *Ta* was higher at AWS 303. Similar tendencies can be observed for *Tg* differences between AWS 303, AWSs 302 and 304 (Fig. 5B). The results show that from 9.00 UTC to 14.00 UTC, *Tg* was constantly lower at AWS 303 (from 0 °C to 16.5 °C) than at AWS 302, or similar (from -3 °C to 5.8 °C) to AWS 304. However, after 14.00 UTC, until late afternoon, the *Ta* values were in both cases higher at AWS 303 with thresholds up to 14.8 °C (AWS 302) and 12.5 °C (AWS 304). Figure 6A presents the *Ta* differences between AWSs during night-time, and the results show minimal differences to AWS 303, i.e. they mostly range from 0 °C to ± 1 °C. Greater *Ta* differences between AWS 303 and other AWSs started to appear with the sunrise time. Figure 6B shows the *Tg* differences during night-time, when the values captured at AWS 303 were constantly lower than those obtained at AWSs 302 and 304. The *Tg* values captured at AWS 303 were lower by 2 °C, with a tendency for the difference to increase to 10 °C after the sunrise time.

Thermal transmittance results for green roofs

All three measurements (*M1*, *M2*and*M3*) were carried out during the winter season, when heating was provided, so as to reach the minimal temperature difference required (15 °C or higher) between indoor and outdoor air. Two sets of heat flux sensors were used to determine the *U* value.

Since this research aimed to determine the influence of additional roof layers on the *U* value, the following

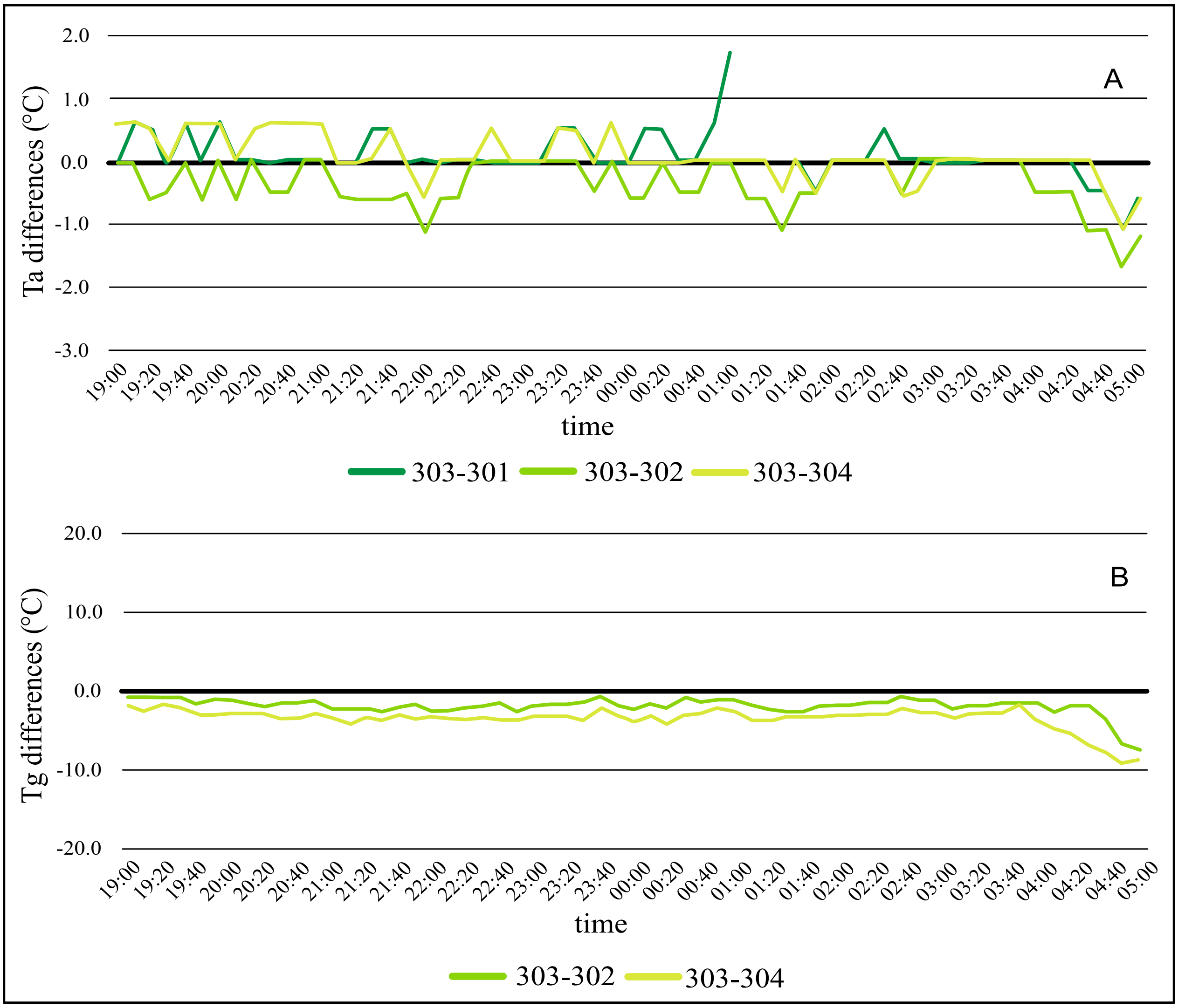

Fig. 6 Thermal differences (in °C) between AWSs during the hottest night-time (July 23rd/24th, from 19:00 to 5:00 UTC) during the heatwave in July 2022, **A** *Ta* differences; **B** *Tg* differences

conclusions have been made from the results presented in Table 3: (a) by applying a 20 cm thick insulation layer on the non-isolated flat roof, the *U* values decreased from 75% to 78% (Fig. 7); (b) by applying a green roof with a 8 cm thick substrate at the top of a refurbished flat roof, more savings could be achieved because the *U* values decreased from 50% to 69%, as registered by two different heat flux sensors; (c) since the *U* value of building elements indicates energy loss, the insulation layer and the green roof can significantly prevent heat loss through flat roofs; (d) the differences in the *U* values from two sensors during the last measurement can be easily explained by the position of the sensors, as the roof was heavily isolated during the last measurement (*M3*), and therefore, thermal bridges were not visible when using infrared thermography (Fig. 3C); on the other hand, they can be easily avoided on non-insulated roofs (Fig. 3B).

Discussion

In this study, the influence of NBSs on the improvement of thermal conditions on a micro-scale and the energy demand of buildings was assessed using extensive green roofs as an example. AWSs were placed around the school building in Novi Sad with the intention of identifying thermal influences from different types of surfaces and materials, i.e. they were deployed to monitor microclimate characteristics near or above the green surface, solar cells, walls and concrete. The focus of this study is to identify the impact of different green or artificial surfaces on thermal conditions, particularly during hot days and

Table 3 Summarized measurement results of the *U* value of the flat roof for three different conditions regarding the roof layers

Measurement description	Measurement period	Average outdoor temperature °C	Average indoor temperature °C	Average temperature difference °C	*U* value (sensor set 1) W/m^2K	*U* value (sensor set 2) W/m^2K	Difference between sensors %	Difference regarding previous condition of flat roof—sensor set 1 %	Difference regarding the previous condition of flat roof—sensor set 2 %
M1—flat roof before building energy refurbishment	20.12.2019–2.1.2020	5.36	27.45	22.09	1.4993	1.6384	−9%	–	–
M2—flat roof after application of thermal insulation	5.1.2021–28.1.2021	3.93	27.81	23.88	0.3706	0.3645	2%	75%	78%
M3—flat green roof	20.1.2023–2.2.2023	1.97	17.75	15.78	0.1156	0.1823	−58%	69%	50%

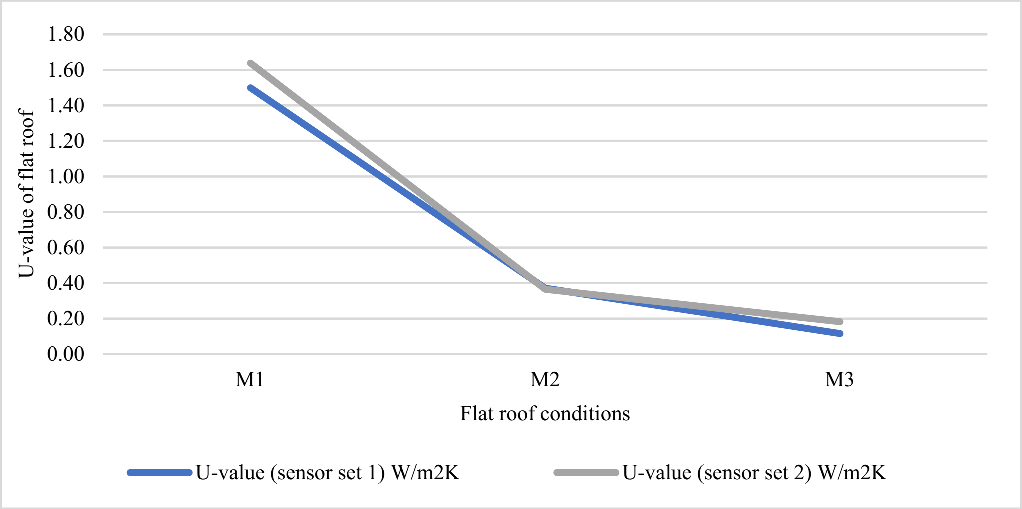

Fig.7 Decreased initial *U* values (*M1*) after the application of the insulation layer (*M2*) and the green roof (*M3*)

heatwaves. The *Ta* and especially *Tg* values were lower (by about 1 °C to 2 °C) at AWS 303 (above the green roof) than at other AWSs, particularly in case of the *Min* and *Average* indices (Table 1). Furthermore, the thermal assessment during daytime and night-time on very hot days shows more significant differences in *Ta* and *Tg* (Table 2, Figs. 5 and 6). Interestingly, the *Ta* and *Tg* differences between AWS 303 and other AWSs during daytime vary from negative to positive values depending on the daytime period, but constant negative difference values (*Tg*, lower values on the AWS 303) were captured during night-time, and they ranged from −0.5 °C to −4 °C (Fig. 6b). These results indicate that an extensive green roof (with a 7.5 cm thick soil substrate and low vegetation—sedum mix), could contribute to better microclimate conditions, especially in terms of reducing thermal discomfort events during hot days, and even more during tropical nights. The daytime *Ta* and *Tg* results indicate that thermal differences between micro-locations are due to the direct influence of shadow or sunlight. As shown in Fig. 5a, AWSs 301 and 302 were exposed to sunlight from the morning (9.00 UTC) to the afternoon (15.00 UTC), and AWSs 303 and 304 were in the shadow of the buildings and trees for most of the period. After 15.00 UTC, AWSs 301, 302 and 304 were in the shadow of trees and buildings on the south and west sides, while AWS 303 was still exposed to sunlight until sunset because of its relative height. The constantly lower *Tg* values from AWS 303 (above the green roof) throughout night-time can be explained by the different capacity of heat absorption and the upward longwave radiation intensities of various surfaces. Obviously, the outcomes of this study are generally in line with the literature data [52, 53], confirming that various artificial surfaces, green/blue surfaces and urban designs can lead to different climate/thermal situations on a local- and micro-scale in cities. Therefore, it can be confirmed that a green infrastructure could have a positive impact on thermal comfort conditions on the micro-environmental level [26–28]. Based on a multi-type green infrastructure evaluation in Toronto (Canada) based on monitoring over two summers, green roof systems ensure an average reduction of the near surface air temperature by 0.8 °C [6]. Another study conducted in the same city (Toronto) shows a general reduction of CO_2 near a green infrastructure of up to 6% [3]. The results of this study are generally consistent with the previous works confirming the cooling potential of heat mitigation and the thermal energy reduction in buildings in Singapore [54], Utrecht [55], Beijing [56], Baltimore–Washington metropolitan area [57], particularly during extreme heat conditions. In addition, previous studies focusing on micro-environmental areas in Novi Sad, confirm that green infrastructures, as well as building shadows, could contribute to preventing outdoor thermal discomfort conditions [58–60]. Likewise, some studies show that urban trees and intensive green infrastructures are more effective in reducing outdoor thermal values than green roofs or green walls [61, 62].

The measurements carried out in Osijek focused mainly on the thermal transmittance properties of the flat roof. The accurate identification of the thermal properties of existing building components can be challenging, especially for historic and heritage buildings, due to their technological complexity and heterogeneity of material deterioration [63]. Thermal transmittance properties can be influenced by occupant activities and behaviour, changes to the material and design, ageing, construction defects, technological performance, building operation and maintenance [63–66]. Studies have demonstrated that minor alterations in thermal transmittance (*U* value, W/m2K), which is a significant parameter for forecasting energy usage, can lead to a substantial shift in heating requirements [67, 68]. As expected, the actions taken on the building in Osijek led to an decreased energy demand, i.e. a decreased *U* value of the flat roof due to the implementation of thermal insulation and later a green roof. By reducing the *U* values of building elements, energy demands are reduced, leading to reduced operational building costs and CO_2 emissions. According to the study “Estimation of benefits and costs from the GReENERGY project” [69], the general reduction of CO_2 emission from both public objects in Novi Sad (Republic of Serbia) and Osijek (Republic of Croatia) amounted to 298.6 t/per year, and the cost savings ranged from 12.000 EUR in 2021 to 18.000 EUR in 2034.

To conclude, the averaged *U* value from two sensor sets can be used. The average *U* value for the flat roof before the energy refurbishment of the building was 1,5689 W/m_2K; for the flat roof after thermal insulation, the *U* value was 0,3676 W/m^2K and 0,1490 W/m^2K for the flat green roof. That means that the *U* value for the flat green roof is by 59% lower than the value for the insulated roof, and it is by 91% lower than the value for the flat roof before energy refurbishment. The values presented here can be multiplied by the surface of the flat roof (160 m^2), with respect to the average temperature difference during the measurement, and can be used to calculate energy savings (in kW or kWh if multiplied by numbers of the building’s operational hours) for 1 year.

The feasibility and future of applying nature-based solutions to decrease the energy demand in public buildings

The implementation of NBSs requires an in-depth feasibility study to evaluate the economic, ecological and energetic benefits of the applied solutions. Before applying adaptations on the two public buildings in Osijek and Novi Sad, a feasibility study was carried out to prove that an actual decrease in the overall amount of required electricity and CO_2 emissions would occur. This decrease was made possible by implementing two principles in both facilities: (a) decreasing energy demand by reconstructing buildings and (b) generating own energy per se, using photovoltaic power plants. In a public building in Osijek, the required amount of electricity per year, according to its energy certificate, was 382.111.60 kWh. After the adaptations (building reconstruction + green roof implementation), the amount decreased to 171.202.80 kWh, which is less than half of the initial requirements.

According to the energy certificate for the same building, the usable surface of the heated area is 878.65 m^2 with the specific emission of CO_2 of 121 kg/(m^2a) per year, or 106.32 t per year. Since the surface area after the reconstruction (building reconstruction + green roof implementation) remained the same, the amount of the specific emission of CO_2 decreased to 50 kg/(m^2a), which is equal to 43 t per year (instead of the initial 106.32 t) [69].

Although this paper presents the results of specific examples of NBS implementation, there are still topics that could be discussed in future adaptations of this kind. The problem that should be addressed is power plant selection. At the moment, there is no information about whether the current power plant can reach its maximum potential, or a more suitable one would be a better choice. To provide information about the best choice per specific micro-location, additional measurements and analysis should be performed. To achieve this, additional monitoring data from the current power plant dataloggers should be combined with micro-meteorological measurements provided from AWSs, bringing together the results regarding the financially most suitable type and the power of solar panels for specific micro-climate locations.

Conclusions

This study presents the results of the assessments of microclimate conditions and the thermal transmittance of/around public buildings in Novi Sad (Republic of Serbia) and Osijek (Republic of Croatia) based upon multi-year monitoring data sets from different seasons. Based upon its outcomes, it can be concluded that green infrastructure, known as NBS—in this case, an extensive green roof—has an impact on diverse aspects of urban environments and the energy conditions of buildings. The positive effects are visible both in summer periods and during the winter season. The results show that extensive green roofs can slightly improve thermal conditions on a micro-scale during hot days, as well as that the green infrastructure is particularly effective during tropical nights. In addition, the 8 cm thick extensive green roof can contribute to energy efficiency during the winter season by improving the thermal transmittance of building walls and ceilings. In both cases, the green infrastructure is helpful in improving the outdoor thermal comfort conditions, urban biodiversity, using less heating energy and preventing increased CO_2 emissions (public buildings use gas or oil and in some cases coal or electric power for heating).

Therefore, this kind of monitoring and assessment can help local communities in their struggle against carbon emissions, which endanger the urban environment, and it can serve as a good example of the implementation of NBSs on the local or micro level. In addition, this research is in line with the Agenda 2030, which defines 17 different Sustainable Development Goals (SDGs), but it primarily focuses on the following: SDG 3—an increased awareness of the necessity of improving public healthcare through the monitoring and improvement of thermal outdoor comfort conditions; SDG 11—contributing to a better implementation of climate-conscious urbanisation that can improve the quality of life, microclimate conditions and contribute to the development of carbon–neutral cities; and SDG 13—work on further measures towards the adaptation to climate change, especially in urban areas where the microclimate and local climate are additionally modified due to the impact of urbanisation.

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Author contributions
SS and HK created the concept and wrote the manuscript. IŠ worked on data sets preparation and visualization. JD wrote the manuscript. All authors read and approved the final manuscript.

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The authors declare no competing interests.

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References

1. Cassetti G, Boitier B, Elia A, Le Mouel P, Gargiulo M, Zagame P, Nikas A, Koasidis K, Doukas H, Chiodi A (2023) The interplay among COVID-19 economic recovery, behavioural changes, and the European Green Deal: an energy-economic modelling perspective. Energy 263:125798. https://doi.org/10.1016/j.energy.2022.125798
2. Al-Saidi M (2023) White knight or partner of choice? The Ukraine war and the role of the Middle East in the energy security of Europe. Energy Strateg Rev 49:101116. https://doi.org/10.1016/j.esr.2023.101116
3. Colgan JD, Gard-Murray AS, Hinthorn M (2023) Quantifying the value of energy security: how Russia's invasion of Ukraine exploded Europe's fossil fuel costs. Energy Res Soc Sci 103:103201. https://doi.org/10.1016/j.erss.2023.103201
4. Knez S, Štrbac S, Podbregar I (2022) Climate change in the Western Balkans and EU Green Deal: status, mitigation and challenges. Energy Sustain Soc 12:1. https://doi.org/10.1186/s13705-021-00328-y
5. Stevanović M, Pavlićević P, Vujinović N, Radovanović M (2023) International relations challenges and sustainable development in developing countries after 2022: conceptualization of the risk assessment model. Energy Sustain Soc 13:48. https://doi.org/10.1186/s13705-023-00430-3
6. Ignjatović J, Filipović S, Radovanović M (2024) Challenges of the green transition for the recovery of the Western Balkans. Energy Sustain Soc 14:2. https://doi.org/10.1186/s13705-023-00421-4

7. Leonard M, Pisani-Ferry J, Shapiro J, Tagliapietra S, Wolff Guntram B (2021) The geopolitics of the European Green Deal. Bruegel Policy Contribution, No. 04/2021, Bruegel, Brussels. http://hdl.handle.net/10419/237660)
8. Bäckstrand K (2022) Towards a Climate-Neutral Union by 2050? The European green deal, climate law, and green recovery. In: BakardjievaEngelbrekt A, Ekman P, Michalski A, Oxelheim L (eds) Routes to a Resilient European Union. Palgrave Macmillan, Cham. https://doi.org/10.1007/978-3-030-93165-0_3
9. Economidou M, Todeschi V, Bertoldi P, D'Agostino D, Zangheri P, Castellazzi L (2020) Review of 50 years of EU energy efficiency policies for buildings. Energ Buildings 225:110322. https://doi.org/10.1016/j.enbuild.2020.110322
10. Camarasa C, Nägeli C, Ostermeyer Y, Klippel M, Botzler S (2019) Diffusion of energy efficiency technologies in European residential buildings: a bibliometric analysis. Energ Buildings 202:109339. https://doi.org/10.1016/j.enbuild.2019.109339
11. Pietrapertosa F, Tancredi M, Giordano M, Cosmi C, Salvia M (2020) How to prioritize energy efficiency intervention in municipal public buildings to decrease CO$_2$ emissions? A case study from Italy. Int J Env Res Pub He 17:4434. https://doi.org/10.3390/ijerph17124434
12. Munguia N, Esquer J, Guzman H, Herrera J, Gutierrez-Ruelas J, Velazquez L (2020) Energy efficiency in public buildings: a step toward the UN 2030 Agenda for Sustainable Development. Sustainability 12:1212. https://doi.org/10.3390/su12031212
13. Croatia - Country Commercial Guide. 2023 https://www.trade.gov/country-commercial-guides/croatia-energy#:~:text=According%20to%20Eurostat%2C%20gross%20primary,renewables%2C%20primarily%20large%20hydropower%20plants. Accessed 6 Feb 2024
14. Energy Strategy for the period until 2030, with an outlook through 2050, N. 25/2020, Editor. 2020: Zagreb. (in Croatian: Strategija energetskog razvoja Republike Hrvatske do 2030. godine, s pogledom na 2050. godinu)
15. Tommerup H, Rose J, Svendsen S (2007) Energy-efficient houses built according to the energy performance requirements introduced in Denmark in 2006. Energ Buildings 39(10):1123–1130. https://doi.org/10.1016/j.enbuild.2006.12.011
16. Directive 2010/31 EU of the European Parliament and the Council of 19 May 2010 on the energy performance of buildings. Official Journal of the European Communities, L 153/21-2
17. Ghazi KW, Binder B, Zimmermann M, Tanner Ch (2014) Efficiency verification of a combination of high performance and conventional insulation layers in retrofitting a 130-year old building. Energ Buildings 82:237–242. https://doi.org/10.1016/j.enbuild.2014.06.050
18. Krstić H, Koški Ž, IštokaOtković I, Španić M (2014) Application of neural networks in predicting airtightness of residential units. Energ Buildings 84:160–168. https://doi.org/10.1016/j.enbuild.2014.08.007
19. Translation: Technical Regulation on the Rational Use of Energy and Thermal Insulation in Buildings. „Narodne novine" broj 128/15, 70/18, 73/18, 86/18, 102/20. (in Croatian: Tehnički propis o racionalnoj uporabi energije i toplinskoj zaštiti u zgradama)
20. Statistical Office of Republic of Serbia. https://www.stat.gov.rs/media/358492/balance-of-electricity-in-2021.pdf. Accessed 7 Feb 2024
21. International Renewable Energy Agency (IRENA). https://www.irena.org/-/media/Files/IRENA/Agency/Statistics/Statistical_Profiles/Europe/Serbia_Europe_RE_SP.pdf. Accessed 7 Feb 2024
22. INECP (2023) Integrated National Energy and Climate Plan of the Republic of Serbia for the period 2030 with the projections up to 2050. https://www.energy-community.org/dam/jcr:01992fc5-4981-4ee3-84f8-f1f96830b4ba/INECP_Serbia_ENG_13.06.23%20.pdf. Accessed 7 Feb 2024

23 Geneletti D, Cortinovis C, Zardo L, Esmail BA (2020) Planning for ecosystem service in cities. Springer Open, Switzerland, p 96

24. Castellar JAC, Popartan LA, Pueyo-Ros J, Atanasova N, Lanergraber G, Säumel I, Corominas L, Comas J, Acuna V (2021) Nature-based solutions in the urban context: terminology, classification and scoring for urban challenges and ecosystem services. Sci Total Environ 779:146237. https://doi.org/10.1016/j.scitotenv.2021.146237
25. Anderson V, Gough WA (2020) Evaluating the potential of nature-based solutions to reduce ozone, nitrogen dioxide, and carbon dioxide through a multi-type green infrastructure study in Ontario, Canada. City Environ Interact 6:100043. https://doi.org/10.1016/j.cacint.2020.100043
26. Anderson V, Gough WA, Agic B (2021) Nature-based equity: An assessment of the public health impacts of green infrastructure in Ontario Canada. Int J Env Res Pub He 18:5763. https://doi.org/10.3390/ijerph18115763
27. Anderson V, Gough WA (2022) Typology of nature-based solutions for sustainable development: an analysis of form, function, nomenclature and associated applications. Land-Basel 11:1071. https://doi.org/10.3390/land11071072
28. Anderson V, Gough WA (2022) Nature-based cooling potential: a multi-type green infrastructure evaluation in Toronto, Ontario, Canada. Int J Biometeorol 66:397–410. https://doi.org/10.1007/s00484-021-02100-5
29. Iungman T, Cirach M, Marando F, Pereira Barboza E, Khomenko S, Masselot P, Quijal-Yamorano M, Mueller N, Gasparrini A, Urquiza J, Heris M, Thondoo M, Nieuwenhuijsen M (2023) Cooling cities through urban green infrastructure: a health impact assessment of European cities. Lancet 401:577–589. https://doi.org/10.1016/S0140-6736(22)02585-5
30. European Commission, Research and innovation, Brussels, Belgium. Available via https://commission.europa.eu/research-and-innovation_en?pg=nb. Accessed 27 Nov 2023
31. He Q, Tapia F, Reith A (2023) Quantifying the influence of nature-based solutions on building cooling and heating energy demand: a climate specific review. Renew Sust Energ Rev 186:113660. https://doi.org/10.1016/j.rser.2023.113660
32. Mata TM, Oliveira GM, Monteiro H, Silva GH, Caetano NS, Martins AA (2021) Indoor air quality improvement using nature-based solutions: design proposals to greener cities. Int J Env Res Pub He 18:8472. https://doi.org/10.3390/ijerph18168472
33. Sowińska-Świerkosz B, García J (2021) A new evaluation framework for nature-based solutions (NBS) projects based on the application of performance questions and indicators approach. Sci Total Environ 787:147615. https://doi.org/10.1016/j.scitotenv.2021.147615
34. European Commission, The European Grean Deal, Brussels, Belgium. Available via https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en. Accessed 27 Nov 2023
35. European Commission, New European Bauhaus, Brussels, Belgium. Available via https://new-european-bauhaus.europa.eu/about/about-initiative_en. Accessed 27 Nov 2023
36. Somarakis G, Stagakis S, Chrysoulakis N (2019) Thinknature Nature-Based Solutions Handbook. ThinkNature project funded by the EU Horizon 2020 research and innovation programme.
37. GReENERGY project, available via www.greenenergy.rs. Accessed 27 Nov 2023
38. Kottek M, Grieser J, Beck C, Rudolf B, Rubel F (2006) World Map of the Koppen-Geiger climate classification updated. Metorol Z 15:259–263. https://doi.org/10.1127/0941-2948/2006/0130
39. Croatian Meteorological and Hydrological Service. https://meteo.hr/index_en.php. Accessed 6 Nov 2023
40. Savić S, Krstić H, Dunjić J, Milošević D, Šećerov I, Kukić S (2021) Greening the cites – Development and promotion of the green energy, energy efficiency and sustainable environment in cities. University of Novi Sad, Faculty of Sciences, Department of Geography, Tourism and Hotel Management, Novi Sad-Osijek, 110 pp. http://www.greenenergy.rs/_files/_publications/Publikacija_ENG_final.pdf. Accessed 6 Nov 2023.
41. Statistical Office of the Republic of Serbia (2023) Age and sex. Data by settlements. Book 2. 2022 Census of Population, Households and Dwellings. Belgrade. https://popis2022.stat.gov.rs/sr-latn/5-vestisaopstenja/news-events/20230525-starost-i-pol/. Accessed 6 Nov 2023
42. Savić S, Krstić H, Milošević D, Dunjić J, Šećerov I, Lazić L, Arsenović D (2023) Greening the cities – Improving micro-scale thermal conditions and enhancing sustainable urban environment. International Conference „The circular economy: „the number of priority" for the European Green Deal", 19–21 September 2022, Novi Sad, Serbia:254–264. ISBN: 978-619-04-0001-1
43. Republic Hydrometeorological Service of Serbia. https://www.hidmet.gov.rs/index_eng.php. Accessed 6 Nov 2023.
44. Testo Globe sensor, https://www.designingbuildings.co.uk/wiki/Globe_temperature. Accessed 6 Nov 2023.
45. Unger J, Skarbit N, Gál T (2018) Evaluation of outdoor human thermal sensation of local climate zones based on long-term database. Int J Biometeorol 62:183–193. https://doi.org/10.1007/s00484-017-1440-z
46. Milošević D, Trbić G, Savić S, Popov T, Ivanišević M, Marković M, Ostojić M, Dunjić J, Fekete R, Garić B (2022) Biometeorological conditions during hot

summer days in diverse urban environments of Banja Luka (Bosnia and Herzegovina). Geographica Pannonica 26:29–45. https://doi.org/10.5937/gp26-35456
47. Milošević D, Savić S, Kresoja M, Lužanin Z, Šećerov I, Arsenović D, Dunjić J, Matzarakis A (2022) Analysis of air temperature dynamics in the 'local climate zones' of Novi Sad (Serbia) based on long-term database from an urban meteorological network. Int J Biometeorol 66:371–384. https://doi.org/10.1007/s00484-020-02058-w
48. Deutscher Wetterdienst, Hot days definition. https://www.dwd.de/EN/ourservices/germanclimateatlas/explanations/elements/_functions/faqkarussel/heissetage.html. Accessed 6 Nov 2023
49. International Organization for Standardization. Thermal insulation. Building elements. In-situ measurement of thermal resistance and thermal transmittance. Part 1: Heat flow meter method (ISO 9869-1:2014). https://www.iso.org/standard/59697.html. Accessed 27 Nov 2023
50. Albatici R, Tonelli AM (2008) On site evaluation of U-value of opaque building elements: a new methodology. Passive and Low Energy Architecture (PLEA) Conference, Dublin, Ireland. 2008
51. Doran S (2000) Safety and health business plan – field investigations of the thermal performance of construction elements as built. BRE, Building Research Establishment Ltd., East Kilbride
52. Middel A, Krayenhoff ES (2019) Micrometeorological determinants of pedestrian thermal exposure during record-breaking heat in Tempe, Arizona: introducing the MaRTy observational platform. Sci Total Environ 687:137–151. https://doi.org/10.1016/j.scitotenv.2019.06.085
53. Lehnert M, Savić S, Milošević D, Dunjić J, Geletič J (2021) Mapping local climate zones and their applications in European urban environments: a systematic literature review and future development trends. ISPRS Int J Geo-Info 10:260. https://doi.org/10.3390/ijgi10040260
54. Yang J, Kumar DLM, Pyrgou A, Chong A, Santamouris M, Kolokotsa D, Lee SE (2018) Green and cool roofs' urban heat island mitigation potential in tropic climate. Sol Energy 173:597–609. https://doi.org/10.1016/j.solener.2018.08.006
55. Solcerova A, van de Ven F, Wang M, Rijsdijk M, van de Giesen N (2017) Do green roofs cool the air? Build Environ 111:249–255. https://doi.org/10.1016/j.buildenv.2016.10.021
56. Feng Y, Wang J, Zhou W, Li X, Yu X (2022) Evaluationg the cooling performance of green roofs under extreme heat conditions. Front Env Sci-Switz 10:874614. https://doi.org/10.3389/fenvs.2022.874614
57. Li D, Bou-Zeid E, Oppenheimer M (2014) The effectiveness of cool and green roofs as urban heat island mitigation strategies. Environ Res Lett 9:055002. https://doi.org/10.1088/1748-9326/9/5/055002
58. Bajšanski I, Milošević D, Savić S (2015) Evaluation and improvement of outdoor thermal comfort in urban areas on extreme temperature days: applications of automatic algorithms. Build Environ 94:632–643. https://doi.org/10.1016/j.buildenv.2015.10.019
59. Milošević D, Bajšanski I, Savić S (2017) Influence of changing trees locations on thermal comfort on street parking lot and footways. Urban For Urban Gree 23:113–124. https://doi.org/10.1016/j.ufug.2017.03.011
60. Stojaković V, Bajšanski I, Savić S, Milošević D, Tepavčević B (2020) The influence of changing location of trees in urban green spaces on insolation mitigation. Urban For Urban Gree 53:126721. https://doi.org/10.1016/j.ufug.2020.126721
61. Zölch T, Maderspacher J, Wamsler C, Pauleit S (2016) Using green infrastructure for urban climate-proofing: an evaluation of heat mitigation measures at the microscale. Urban For Urban Green 20:305–316. https://doi.org/10.1016/j.ufug.2016.09.011
62. Erell E (2017) Urban Greening and Microclimate Modification. In: Tan, P., Jim, C. (eds) Greening Cities. Advances in 21st Century Human Settlements. Springer, Singapore. https://doi.org/10.1007/978-981-10-4113-6_4
63. Lucchi E (2017) Thermal transmittance of historical brick masonries: a comparison among standard data, analytical calculation procedures, and in situ heat flow meter measurements. Energ Buildings 134:171–184. https://doi.org/10.1016/j.enbuild.2016.10.045
64. Cuerda E, Guerra-Santin O, Romero Herrera NA, Neila J (2016) Evaluation and Comparison of Building Performance in Use through On-Site Monitoring nd Simulation Modelling. Proceedings of the 3rd IBPSA-England Conference BSO 2016, Great North Museum, Newcastle.
65. Gori V, Marincioni V, Biddulph P, Elwell CA (2017) Inferring the thermal resistance and effective thermal mass distribution of a wall from in situ measurements to characterise heat transfer at both the interior and exterior surfaces. Energ Buildings 135:398–409. https://doi.org/10.1016/j.enbuild.2016.10.043
66. Bros-Williamson J, Garnier C, Currie JI (2016) A longitudinal building fabric and energy performance analysis of two homes built to different energy principles. Energ Buildings 130:578–591. https://doi.org/10.1016/j.enbuild.2016.08.052
67. Majcen D, Itard L, Visscher H (2013) Actual and theoretical gas consumption in Dutch dwellings: what causes the differences? Energ Policy 61:460–471. https://doi.org/10.1016/j.enpol.2013.06.018
68. Majcen D, Itard LCM, Visscher H (2013) Theoretical vs. actual energy consumption of labelled dwellings in the Netherlands: discrepancies and policy implications. Energ Policy 54:125–136. https://doi.org/10.1016/j.enpol.2012.11.008
69. Šandrk Nukić I, Krstić H, Savić S (2020) Procena koristi i troškova GReENERGY projekta. Estimation of benefits and costs of the GReENERGY project. Josip Juraj Strossmayer University of Osijek, Faculty of Civil Engineering and Architecture Osijek, Osijek-Novi Sad, 46 pp. http://www.greenenergy.rs/_files/_publications/CBA_Gre_SER.pdf. Accessed 6 Nov 2023

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