Urban heat island phenomenon in Central Europe

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1 ABSTRACT

The urban heat island (UHI) phenomenon is characterized by significantly higher temperatures in metropolitan areas as compared to the surrounding suburban and rural neighborhoods. In this context, this paper presents a preliminary report pertaining to an ongoing EU-supported research project, which investigates the urban heat island phenomena in Central Europe. First, the background and general scope of the UHI phenomena are discussed. Subsequently, the paper investigates the manifestation of the urban heat islands phenomena (especially in the city of Vienna) and evaluates possible mitigation and adaptation strategies.

2 INTRODUCTION AND BACKGROUND

The urban heat island (UHI) phenomenon is characterized by significantly higher temperatures in metropolitan areas as compared to the surrounding suburban and rural neighborhoods. The intensity of urban heat islands is believed to rise proportionally to the dimension and population of the urban setting. Given the ongoing population increase in urban areas worldwide, it is expected that the severity of challenges associated with UHI will become increase. Furthermore, the UHI effects are directly related to (and worsened by) the climate change phenomena. Hence, it is expected that the expected further increase of the global temperatures would more immediately and strongly affect the habitability of urban spaces. Additionally, higher air temperatures directly influence energy use due to increased reliance on air conditioning in buildings.

In this context, this paper presents the results of an ongoing EU-supported research project, which investigates the urban heat island phenomena in Central Europe (UHI 2011). First, the main contributing factors of the UHI phenomena are discussed. Subsequently, the paper investigates on the manifestation of the urban heat islands phenomena (especially in the city of Vienna) and evaluates possible mitigation and adaptation strategies (material properties, green roofs and cool roofs).

2.1 What are the main contributing factors

Causes for higher prevailing temperatures in the city compared to rural areas are manifold. Influencing factors regarding the formation of the urban heat island effect can be understood by evaluating the surface energy balance between urban and rural area of a city. The surface energy balance can be described by the following equation (Erell et al. 2011):

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A \qquad (1)$$

Where Q^* is net wave radiation, Q_F is anthropogenic heat flux, Q_H is convective sensible heat flux, Q_E is latent heat flux, ΔQ_S is net storage heat flux, and ΔQ_A is advection.

According to Oke (1982):

- Cities or densly populated areas show typically an increase in net radiation, due to higher absorption of short-wave radiation by dark surfaces such as dark plasters, and black asphalt. Furthermore, densly built up areas and surface geometries lead to multiple reflections in the urban canyons which further increase the absorption of the short-wave radiation. On the other hand, long-wave radiation of the surfaces back to the sky during night hours can be reduced since densly built areas tend to have lower sky view factors and net wave radiation is trapped in the urban structure.

- Additional heat emissions caused by transportation, industrial processes, as well as heating, and cooling in the urban structure result in high levels of anthropogenic heat release.
- Buildings tend to slow the average wind speed, which can lead to air temperature increase within the city.
- Construction materials for buildings, roads, pavements, etc., which typically cover a large percentage of the urban surfaces, are in general water-tight. This reduces the evaporation effect in the densely built city areas.
- Urban surfaces tend to store more heat due to material properties (thermal capacity and conductivity).

2.2 How the urban heat island manifests itself

Depending on geographic position and prevailing weather conditions, consequences of urban heat islands may be advantageous or disadvantageous in view of energy use for heating and cooling. According to Taha (1997), heat islands in the areas of high latitude cause fewer problems since they reduce the energy demand for heating. Urban heat island effects are particularly unwanted in regions of low and mid-latitudes because they contribute to an increase in cooling loads (Rosenzweig et al. 2005). Vienna, which has a latitude of 48° is dominated by heating loads but cooling loads are rising. Figure 1 shows the urban heat island intensity expr essed in terms of mean monthly temperatures for January, April, July, and October (data are available at ZAMG 2011). Note that urban heat island intensity is defined here in terms of air temperature difference between measurements made in the central urban areas and immediate rural areas around a city. Results show that the UHI intensity is more pronounced during winter than in summer. However, climate experts investigated that the number of hot days has increased significantly in the last 50 years (Kromp-Kolb 2005). Currently, active cooling is not required in Austria for residential buildings. However, should projected warming trend change this, a dramatic increase in energy demand has to be expected. This underlines the importance of appropriate adaptation and mitigation efforts and their inclusion in urban development processes. Figure 2 shows the comparison of temperature and wind speed of a urban and rural weather station during a very hot 7 day period in the city of Vienna. Temperature maxima lie in the range between 32 and 35°C during this 7 day period. Figure 3 shows the urban heat island intensity between the 2 stations (urban and rural) for the same period. Graphs show that temperature is most of the time higher in the urban area compared to the rural area during the 7 day period. The difference is more pronounced during the night hours, and reaches up to 4K. During the day the urban heat island intensity is not as pronounced. The lowest temperature can be observed in both cases at around 6:00 am and the maximum temperature around 5:00 pm. The urban heat island intensity reaches its maximum typically around 10:00 pm.

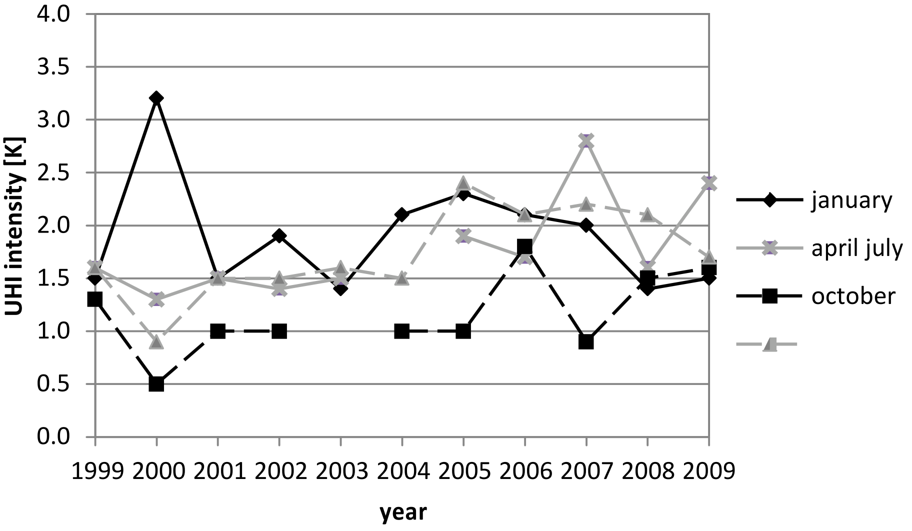


Fig. 1: Urban heat island intensity ($\theta_{urban} - \theta_{rural}$ in K) in terms of mean monthly temperatures for January, April, July, and October (from 1999 to 2009)

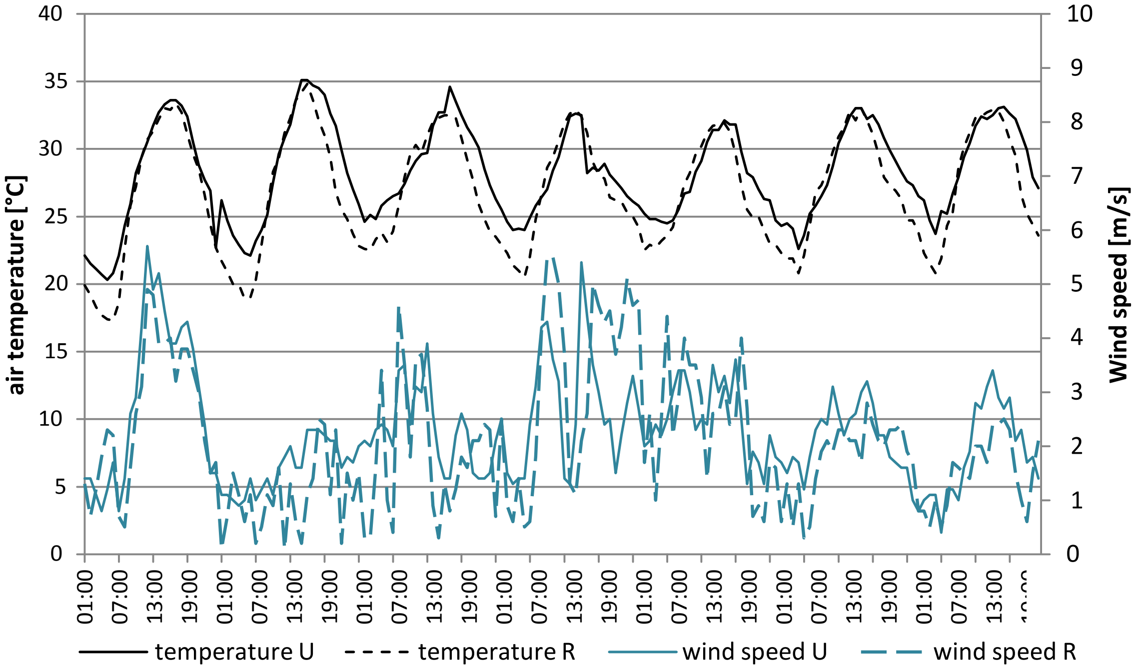


Fig. 2: Mean hourly air temperature and wind speed for urban (U) and rural (R) weather station for 7 days in the city of Vienna (July 2006)

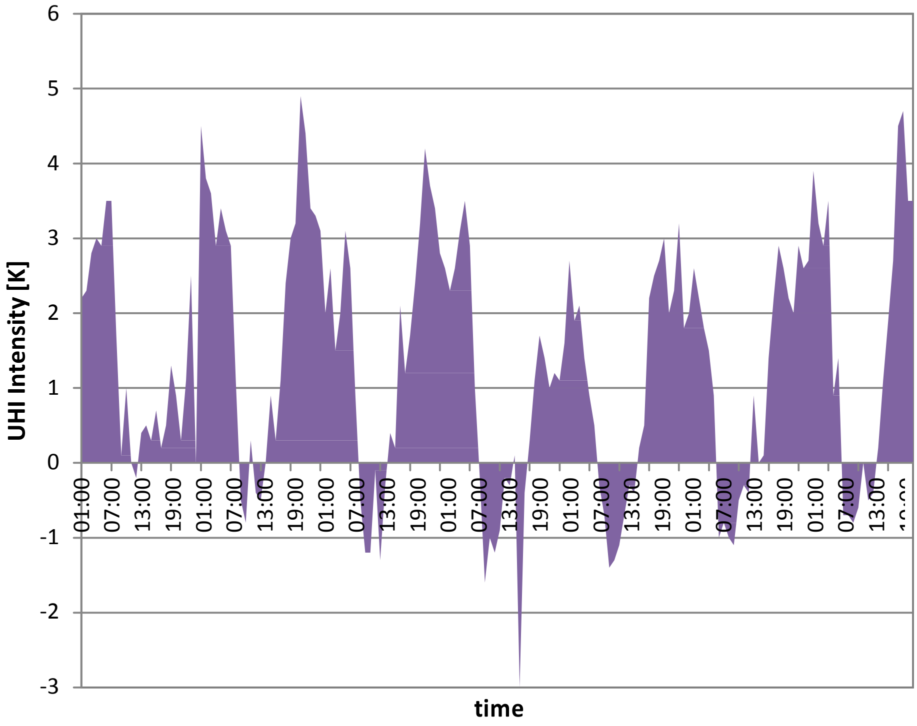


Fig. 3: Urban heat island intensity (hourly values of $\theta_{urban} - \theta_{rural}$ in K) for a 7 day periode in the city of Vienna (July 2006)

3 MITIGATION AND ADAPTATION STRATEGIES

UHI phenomenon is wide spread. The awareness about its critical importance is rising as well. Accordingly, measures and strategies are sought after, which would mitigate the UHI phenomanon. Goverments and municipalities need strategies on mitigation and adaptation in order to introduce those in regional and urban planning. Several measures have been discussed in the literature. According to Akbari (2005), Memon et al. (2008), Santamouris (2007), and Taha (1997), most promising measures appear to be the use of vegetation and suitable materials (e.g., for built surfaces). Kleerekoper et al. (2011) suggest that the treatment of surfaces exposed to solar radiation has an effect on the urban microclimate. One of the more common strategies to mitigate the urban heat island effect is to modify the pavements of streets, to add vegetation and, on building scale, to adapt the roofs. In the present contribution, we will focus on material properties and on mitigation strategies concerning buildings' roofs (green roofs, cool roofs).

3.1 Construction Materials

Several material properties including heat storage, evaporation capacity, and radiative properties have a significant influence on the performance of construction materials in connection with the urban climate. As compared to urban areas, surfaces in rural areas involve more frequently low diffusivity materials. Hence more heat is stored during the day and slowly released during the night (Gartland 2008, Oke 2006). Additionally, due to the amount of vegetation and permeable materials, rural areas display high values of evapotranspiration, whereas in urban areas the water runoff is much higher due to the amount of sealed surfaces. Hence, the sensible heat flux increases, while the solar driven evapotranspiration (latent heat flux) decreases (Kleerekoper et al. 2011). Albedo and emissivity pertain to the radiative properties of a material. Albedo is the ratio of radiation reflected from a surface to the incident radiation and therefore determines how much solar energy is absorbed by a material. The higher the albedo of a surface is, the lower the energy absorbed by the material. This means that cities absorb more solar radiation than their rural counterparts and this can lead to an increase in cooling energy use (Alexandri and Jones 2006). The definition of albedo can not only be applied to materials but also to more heterogeneous and complex surfaces like urban areas. The albedos of cities typically range from 0.1 to 0.2 but there are exceptions (Taha 1997). In order to mitigate urban heat islands, these factors should play an important role when choosing materials for new constructions or retrofitting of existing buildings (Grimmond 2007, Wong and Chen 2009).

3.2 Roofs

In sunny and hot conditions, traditional roofing materials can heat up to 90°C. This has negative effects not only on the surrounding but also the building itself: Indoor temperatures rise, indoor comfort is reduced, and more energy for cooling is needed. Furthermore, these high temperatures lead to a shorter lifespan of the roofing material. More appropriate roofing directly influences the cooling load of the building and has an indirect positive effect on the surrounding area. If applied city wide, roofing modification measures could influence the climate of an entire area (Akbari et al. 2001, Gartland 2008).

3.2.1 Cool Roofs

The two most important characteristics of cool roofs are high solar reflectance (high albedo) and high thermal emittance. More than 70% of the solar energy should be reflected by the material and the solar emittance has to be 80% or higher (Gartland 2008). According to Gartland (2008), the surfaces of cool roofs only heat up to 40° to 60°C. Berdahl and Bretz (1997) found a temperature difference between ambient air temperature and surface temperature of traditional roofing materials of 50 K and for cool roofs of around 10 K. Hence, if a "cool material" is applied to a building, the heat flux into the building is decreased (Santamouris et al. 2011).

Various materials for different construction types can be deployed as cool roofs. Examples are cool coatings (cementitious or elastomeric), cool shingle–ply roofing systems made of different materials, and more traditional roofing systems such as clay shingles with high albedo values (Gartland 2008). Black asphalt surfaces on rooftops can have an initial reflectance of 0.04. The same roof, if covered with a smooth white coating, will have a solar reflectance of 0.80 (Santamouris et al. 2011). Existing rooftops can be painted or covered in order to change the albedo. Usually, choosing a cool roof alternative will add little or no additional cost. This also applies to replacing existing roof surfaces, if incorporated into routine re-roofing and resurfacing schedules (Bretz *et al.* 1998). Additionally, the lifespan of cool roofs is longer than the lifespan of dark roofing materials. The reasons are: lower surface and material temperature and lower temperature differences (Santamouris et al. 2011). Synenefa et al. (2011) observed that the daily fluctuation of surface temperature reaches 25 K for a conventional dark material while for a cool roof it is only 8 K.

Over time the performance of the cool surfaces decreases. A white roof with an initial solar reflectance of 0.80 can – due to dust and biomass deposit – acquire a solar reflectance of only 0.6 (Levinson et al. 2005). Synnefa et al. (2007) suggested that the attenuation was mainly due to dirt and not permanent. Their experiment included outdoor aging of the materials for three month. Afterwards the samples were washed, whereupon 93% of the initial solar reflectance was restored. Therefore, the surfaces need regular maintaining and cleaning. Nevertheless, compared to a conventional roof, cool roofs usually have lower life cycle costs, resulting from a longer lifespan and energy savings (Akbari et al. 2001).

The effects and benefits of cool roofing materials have been documented in many studies. At the building scale, a reduction of cooling energy use and peak energy demand for cooling has been observed. According to a literature review based on 27 articles on the effect of applying cool materials (mainly white roofing) on commercial and residential buildings in different climatic zones (Haberl and Cho 2004), cooling energy savings from 2% and 44% (averaged 20%) were recorded. The peak cooling energy savings were between 3% and 35%. The results depend on the insulation level, the duct placement, and the attic configuration. On the other hand, an increased solar reflectance of the roof can potentially lead to a higher heating energy demand. Akbari and Taha (1992) investigated the performance of cool roofing systems during wintertime and found that the added heating load is far less significant than the corresponding cooling energy savings.

Susca (2012) performed a study on the life cycle assessment of white and black roofs. White roofs were shown to decrease the environmental loads and affect the radiative forcing and the energy consumption. The impact on GWP (global warming potential) is significantly reduced, because of the effect of surface albedo on radiative forcing. Therefore white roofs are to be preferred to black roofs.

The installation of highly reflective building components, in particular roofs, has also been investigated on an urban scale. Oleson et al. (2010) verified the potential to reduce summertime temperatures. Akbari et al. (1997) and Jo (2010) observed a reduced cooling energy use and lower peak cooling loads and Akbari et al. (2001) suggested a decreased probability of blackouts. Taha (2008) and Rosenfeld et al. (1995, 1998) pointed out the potential to improve local air quality and to reduce air pollution. Air pollution is reduced due to the fact that less cooling energy is used and therefore fewer emissions from power plants are produced. Indirectly, the probability of smog formation is decreased.

It can be concluded that highly reflective or cool materials represent an effective way to mitigate the urban heat island effect. Furthermore, they are cost effective and environmentally friendly. The direct benefit for a building can be lower indoor air temperatures and less cooling energy demand. Furthermore, lower surface temperatures can lead to lower outdoor air temperatures, which indirectly also influences the cooling energy demand of a building.

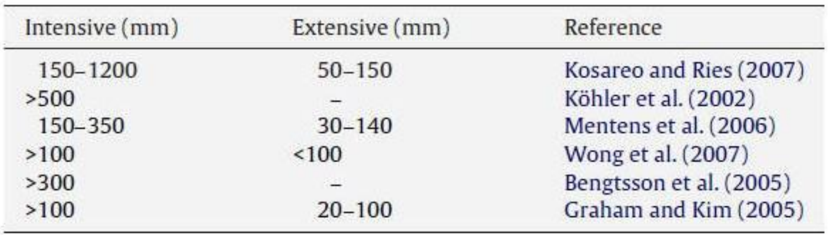
3.2.2 Green roofs

The origin for modern day green roofs goes back to the 1880s in Germany. During a time of rapid industrialization and urbanization, a large stock of inexpensive housing was needed. These buildings were often built with highly inflammable tar as a roofing material. In order to reduce the fire hazard, the roofs were covered with sand and gravel on top. Eventually, seeds naturally colonized these roofs and formed a meadow. In 1980 there were 50 of these roofs – still intact and waterproof – recorded in Berlin (Minke 2000, Getter and Rowe 2006). The lifespan of green roofs was also studied by Porsche and Köhler (2003). They found that the lifespan of green roofs is at least 3 times longer than that of traditional roofs. Green roofs have one key property: low solar absorptance, which leads to lower surface temperatures (Saiz et al. 2006). The surface temperature is on the one hand very important for the performance of the buildings and on the other hand for the surrounding air temperature and therefore for the urban microclimate. Gaffin et al. (2006) suggested that the albedo of a green roofs ranges – similar to that of white roofs – from 0.7 to 0.85, depending on the water availability. But green roofs provide, compared to white roofs, additional advantages in view of rainstorm water runoff and air quality.

Generally there are two major types of green roofs: extensive and intensive green roofs. Table 1 shows examples for soil thickness of intensive and extensive green roofs as defined by different authors. Extensive green roofs consist of a thin (20 to 150 mm) layer of growing medium, thus the size of plants is limited. Walking on extensive roofs is not allowed, due to the shallow and fragile root system of the plants. Furthermore, this roof type requires very low maintenance and it is suitable for European climates. Extensive green roofs are very common, as there are no additional structural supports needed, they represent a convenient solution for retrofitting existing roofs.

For intensive green roof systems the thickness of the growing medium layer starts from 100 mm. This type is often used to create rooftop gardens. Shrubs and even trees can be planted and people can use these green spaces. The dead and life weight of an intensive green roof has a major impact on the structure underneath.

Hence, structural support needs to be considered (Koraseo and Ries 2007, Castleton et al. 2010, Köhler et al. 2002, Mentens et al. 2006, Wong et al. 2007).



Intensive (mm)	Extensive (mm)	Reference
150–1200	50–150	Kosareo and Ries (2007)
>500	–	Köhler et al. (2002)
150–350	30–140	Mentens et al. (2006)
>100	<100	Wong et al. (2007)
>300	–	Bengtsson et al. (2005)
>100	20–100	Graham and Kim (2005)

Table 1. Example soil thickness of intensive and extensive green roofs as defined by different authors (Berndtsson 2010).

A number of studies suggest that there is correlation between an increase in green areas on roofs (and on other building surfaces) and a reduction in local temperature. Rosenzweig et al. (2006) suggested that if 50% of the roofs in New York would be covered with vegetation, the Urban Heat Island intensity would drop by 0.8 K. A simulation conducted by Bass et al. (2003) showed a temperature reduction of 2 K given a green roof coverage of 50% evenly over the city of Toronto. Alexandri (2005) and Alexandri and Jones (2008) pointed out that the potential of lowering the urban air temperature through vegetation on building envelopes is significant. Furthermore they concluded that the impact of vegetation is more significant in hotter and drier climates. However, also humid climates profit from green surfaces. The study suggests that the more the buildings surface is covered with vegetation, the larger the effect. Wong et al. (2007, 2003) pointed out that the impact of green roofs on air temperature depends on the materials used, the thickness of the materials, the water availability, and the plants chosen for the specific site. Furthermore, studies suggest that green roofs could reduce the cooling energy consumption of a building. This could have an indirect positive effect on the Urban heat island, given the beneficial impact of vegetation on the surrounding microclimate. But in case of retrofit, the prior insulation level is also a factor that has to be considered when looking at the energy savings. Castleton et al. (2010) suggested that green roofs can significantly reduce the energy consumption for heating and cooling in poorly insulated buildings, but their effect on newer buildings with better insulation would be far less significant.

The single greatest environmental service provided by green roofs is probably the reduction of rainstorm water runoff (Getter and Rowe 2006) . The increasing number of impermeable (sealed) surfaces in urban areas lead to an increased water runoff. In rural forested or open land hardly any storm water runoff will occur. The water will drain into the ground or return into the atmosphere. In urban areas up to 75% of the rainwater will be surface runoff (Scholz-Barth 2011). When storm water runoff exceeds the capacity of the (combined) sewage system the excess will overflow into relief points, resulting into untreated waste being dumped into rivers (combined sewage overflow) (Getter and Rowe 2006). Green roofs have the ability to retain water and to delay runoff (Berndtsson 2010). The impact depends on design factors such as substrate type and thickness, the type and of plants used. Moreover, the duration and intensity of the rainfall also play an important role. According to Getter and Rowe (200 6), this is probably the greatest environmental service provided by green roofs. Kolb (2004) pointed out that choosing the right substrate is essential for reducing runoff, and that – depending on the rainfall – peak runoff can be reduced by 52% (Kolb 2004). Deutsch and Sullivan (2005) calculated an 80 million liter runoff reduction for the area of Washington, DC, if 20% of buildings that could potentially support green roofs would be actually covered with vegetation. Compared to the overall amount of runoff, the reduction seems not significant (less than 2%), but it leads to significantly fewer combined sewage overflow events. Additionally, the runoff is also delayed by the green roofs, giving the sewage system more time to process the storm water runoff (Getter and Rowe 2006).

Another positive effect of green roofs is the promotion of biodiversity in the urban areas. As most extensive green roofs are inaccessible, they provide an undisturbed habitat for microorganisms, insects, and birds (Getter and Rowe 2006). Brenneisen (2003) performed a biodiversity study of 17 green roofs in Basel. 254 beetle and 78 spider species were identified during the first 3 years. 11% of the beetles and 18% of the spiders found were listed as endangered or rare species. Additionally, on another 90 year old roof in Switzerland rare orchid and other plant species were found (Brenneisen 2003).

It can be concluded, that Green roofs and cool roofs can contribute to improving the performance of buildings concerning energy consumption. Moreover, they can positively influence the urban microclimate. But in addition to the previously mentioned positive effects, the influences of green roofs on the urban environment are manifold, and they depend strongly on the climate, the type of construction and materials used, and the vegetation planted.

4 CONCLUSION

The intensity of urban heat islands rises proportionally to the dimension and population of the urban setting. Given the ongoing population increase in urban areas worldwide, it is expected that UHI implications will become increasingly challenging. Furthermore, the UHI effects are directly related to (and worsened by) the climate change phenomena. Hence, it is expected that an increase in global temperatures would more immediately and strongly affect the habitability of urban spaces. This paper exemplified manifestation of the UHI effect using the instance of Vienna, Austria. Moreover, it discussed – in general terms – UHI mitigation strategies (materials, roofs), arriving at the following conclusions:

- Green roofs and cool roofs can contribute to improving the energy performance of buildings.
- Green roofs and Cool roofs can positively influence the urban microclimate.
- Green roofs can exert a positive effect on the storm water management and improve urban biodiversity.

Such measures do not represent overtly complex building consturction, they are suitable for new construction as well as for retrofitting existing ones. Given the ever growing importance of cities as the primary habitat of world population, the understanding of the UHI phenomena and proper planing and implementation of appropriate mitigation and adaptation measures represent an important and formidable task for all those involved in planning and policy issues in the urban realm.

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