CZECH TECHNICAL UNIVERSITY IN PRAGUE

Faculty of Civil Engineering

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THE ROLE OF GREEN ROOFS IN MITIGATING THE URBAN HEAT ISLAND EFFECT IN DIFFERENT CLIMATE CONDITIONS

VÝZNAM ZELENÝCH STŘECH PŘI ZMÍRŇOVÁNÍ EFEKTU MĚSTSKÝCH TEPELNÝCH OSTROVŮ V ROZDÍLNÝCH KLIMATICKÝCH PODMÍNKÁCH

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I hereby declare that I composed the thesis entirely myself, that it describes my own research and the used ground work is cited in enclosed list.

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ABSTRACT

Green roof infrastructure is gaining popularity in European countries as well as in other countries all over the world. Green roof is more than just soil and plants on a roof but consists of specialized membranes and drainage system to support vegetation on top of buildings. The mitigation of the urban heat islands and the reduction of cooling loads in buildings are the main advantages of this roofing system. Therefore, green roofs can play a significant role in helping cities to adapt to climate changes. In order to demonstrate this role, it is essential to conduct experimental and modeling studies to provide consistent results.

The objective of this research is to evaluate the effects of the green roofs on reduction of excess heat in three urban areas with different climate conditions; Prague, Rio de Janeiro, and Sydney, based on the evidence of occurrence of the heat islands. The effect was examined at a precinct scale; 600 m x 600 m. Modelling testes three scenarios; conventional roof, extensive green roof, and intensive green roof. The methodology consists of seven steps: software validation, modeling, simulation, energy requirement calculation, payback period, data analysis, and conclusion. Data from this simulation is used to demonstrate potential energy savings in case of reduction of energy demand for space cooling.

The results of this research shows that implementation of green roofs is an effective strategy in tackling excess heat on the local neighborhood scale and also in reducing energy demand for cooling during summer period. The data demonstrates that green roofs have a beneficial effect on the urban heat islands by lowering the air temperature within the cities during the summer, in case of Prague by 0.49 °C, Sydney by 0.72 °C, and Rio de Janeiro by 0.92 °C. The most significant reduction was achieved in Sydney and Rio de Janeiro due to their climate condition and urban form. Given these results, green roof infrastructure should be considered as an effective tool by local authorities and city councils in order to improve the quality of living in urban areas and create energy efficient cities.

KEY WORDS: Green roof, Urban heat island effect, ENVI-met, Cooling degree day method

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1 INTRODUCTION

Urbanization is a global trend and in 2014 54 % of people lived in cities that is expected to rise to 66 % by 2050 (United Nations, 2014). Coupled with humanity now predominately living in urban centers it is estimated that 60 % of urban areas projected to exist in 2030 are still to be built (Secretariat of the Convention on Biological Diversity 2012 in Kabisch et al, 2016). How current and future cities accommodate the new population presents challenges from an urban design and liveability perspective.

Growing cities are developing both vertically and horizontally resulting in releasing more anthropogenic heat and higher absorption of solar radiation due to the implementation of impervious materials such as concrete and asphalt. High-rise buildings and narrow streets trap the warmth and reduce air flow. Thus, cities are hotter than their surrounding rural areas. This climatic phenomenon is called the "Urban Heat Island" (UHI) effect, "island" of higher temperatures in the area (Oke, 1987). Urban development has been causing that natural permeable and moist surfaces including grass, plants or bush land become impermeable and dry. Concrete and asphalt heat up during the day and retain the heat and urban infrastructure prevents it from escaping into the cold night. Thus, the UHI increase usage of electric fans and air conditioners for relief of residents. The increased energy demands strain resources which often lead to blackouts or power outages and contribute to an even greater urban heat island effect. For this reason, green infrastructure has emerged as a good proposal to solve this problem, especially in cities. Integrating urban ecology principles into urban development help to increase cities' resilience against heat islands, which are likely to increase due to global climate change (Davies et al., 2017).

One of the opportunities to mitigate the UHI effect comes through the integration of vegetation into the building envelope, for example in form of green roofs. The use of green roofs can provide multiple benefits such as shade, cooling effect through evapotranspiration, and serve as an insulating layer reducing energy consumption and improving thermal comfort. All these factors of green roof can reduce the incoming solar energy up to 90 % (Getter et al, 2006). Hence, green roofs can help to mitigate the UHI effect, reduce the temperatures gains inside the building through its depth, as well as protect against the effect of wind and atmospheric factors such as storms, hail, and ultraviolet radiation. The study of Peck (1999, in Hien et al., 2013) pointed out reducing temperature immediately outside a building can decrease the amount of energy needed for the air conditioner between 50 % and 70 %. With respect to all these characteristics, green roofs have a great potential in temperate, subtropical, and tropical climate conditions.

Despite various efforts in mitigating the UHI effect, there is still a lack of scientific studies, which evaluate the effectiveness of green roofs in different climatic and density variation at a precinct scale. To ensure long-term sustainability and liveability of cities, it is important to conduct precinct scale assessments in order to provide results showing the measure in form of green roofs as effective tool lowering the air temperature.

1.1 OBJECTIVES

The main objective of this thesis is to investigate a contribution of green roofs in mitigating the urban heat island effect in cities. This is achieved through a mixed methods approach. The initial analysis is derived from the use of three dimensional non-hydrostatic model, ENVI-met, that has been designed to module for the simulation of surface-plant-air interactions that has previously been applied to green roofs. The modelling is carried out on three case study locations with different climate conditions and density variation; Prague, Rio de Janeiro, and Sydney. These cities were chosen based on an evidence of the occurrence of the UHI. The second part of the research involves use of the cooling degree day method to quantify the demand for energy needed for space cooling of buildings and to calculate potential energy savings. Based on these energy savings, payback period of green roofs in comparison to conventional roofing is estimated.

ENVI-met software is utilized as the main simulation tool. The investigations of this research are accomplished in two parts. The first part is focused on simulation of an effectiveness of green roofs in specific simplified urban conditions, 600 m x 600 m section in Prague (temperate climate), Rio de Janeiro (tropical climate), and Sydney (subtropical climate) to measure their effectiveness in real conditions. In the second part, the results of simulation are considered. If green roofs can reduce the outdoor air temperature, thereby ameliorate the UHI, it is possible to calculate how much energy can be saved by reduction of half a degree or one degree Celsius. Thus, the outcomes from computer simulation can be utilized to calculate the reduction in energy demand and costs for space cooling.

The purpose of this research intends to show that the implementation of vegetative roofs is an effective strategy in moderating excess heat in urban areas with regard to the liveability of cities and energy savings.

1.2 RESEARCH QUESTIONS

To define the above mentioned objectives of this thesis, the following questions are propounded:

1. Can precinct scale implementation of green roofs reduce the air temperature compared to conventional ones at ground level?
2. What role can precinct scale implementation of green roofs have on mitigating the urban heat island effect?
3. Can precinct scale adoption of green roofs reduce building energy demands for space cooling during summer period?
4. How does an effectiveness of green roofs vary with different climatic and density variation at precinct scale?

The first main question focuses on an effectiveness of vegetated roofs to find out a possible reduction of the air temperature in comparison to conventional roofs. The second question is lined to the first question to discover the potential of green roofs to mitigate the urban heat island effect. Based on findings from the first part of thesis, it is essential to find out the potential of vegetated roof in reduction of energy demand for space cooling. Thus, the third question is defined to provide an answer if greens roofs are an effective tool to decrease the building energy demand. The last question focuses on an effectiveness of installed vegetation on roofs in different climate conditions. To respond to this question, three different case studies with diverse urban density are selected. All these four research questions guide this research.

1.3 METHODS

The role of green roofs in mitigating the urban heat island effect is evaluated by use of the following methods:

Literature review

To elaborate objectives, critical summary of published research literature relevant to a topic of green roof, urban heat island effect, and energy savings is investigated for research. Its purpose is to create familiarity with current thinking and research on a particular topic, and may justify future research into a previously overlooked or understudied area.

Comparative method

To demonstrate an effect of the extensive green roof scenario and the intensive green roof scenario in comparison with the conventional roof scenario in mitigating the urban heat island effect in different climate conditions. The aim of this thesis is demonstrate the contribution of green roofs in case of turning the conventional roofs into green ones at precinct scale. Three cities with different climate condition and urban form are chosen based on the evidence of the occurrence of the urban heat islands. Main purpose of this selection is to demonstrate a diverse potential of vegetated roofs.

Computer simulation

Computer simulation is selected as the main study approach in this research. This work follows a topic of author's Master thesis; its contribution was demonstrated based on field experimental method. The work evaluated the effectiveness of green roofs in mitigating the urban heat island effect through monitoring air and surface temperatures and relative humidity of the green roof and the reinforced concrete flat roof in Rio de Janeiro during the period of February 01 to November 16, 2016. Given this research, it is important to undertake a computer simulation to find out if the obtained results were accurate. The computer simulation tool, which is chosen in this work, is ENVI-met according to the capabilities of this software in modeling greenery and urban fabrics. ENVI-met provide calculation to determine an effectiveness of greenery in many scales. For purpose of this research, the precinct scale is assessed with regard to liveability of cities affected by the UHI. ENVI-met can be used freely for non-commercial simulation studies including application in research, which is capital advantage of this software for this thesis. The simulation in ENVI-met includes three steps: validation of input data, modeling of urban areas of case studies, and simulation.

In order to get accurate data from simulation, ENVI-met takes into consideration wind field, air temperature, humidity, turbulence, radiative fluxes, pollution dispersion, surface and soil temperature, soil water content, vegetation water supply, 3D plant geometry, foliage temperature and exchange process with environment (vegetation interaction with the environment: heat and vapor are exchanged between the plants leafs and the atmosphere). A complex raytracing algorithm is used to analyze the plant impact on solar radiation and on longwave radiation exchange.

Cooling degree day method

To analyse energy demand for space cooling. A detailed analysis of cooling energy use in the future is needed to better understand the impact of the urban heat island effect on building energy consumption. This method is used to evaluate the cost reduction for space cooling during summer period in case of mitigation of elevated air temperature regarding to the implementation of green roofs.

Cooling degree day (CDD) figures come with a base temperature, and provide a measure of how much (in degrees), and for how long (in days) the outdoor air temperature was above that base temperature. CDD is calculated as the sum over each day of the cooling period of the difference between the average daily temperature and reference indoor temperature of 22 °C (based on recommendation of European Environmental Agency).

The data of ENVI-met simulation is considered in order to demonstrate the potential energy savings in case of reduction of energy demand for space cooling based on installation of vegetation on existing roofs.

Discounted payback period

The discounted payback period is the length of time required to recover the cost of an investment based on the investment's discounted cash flows, mostly expressed in years. The discounted payback period takes into consideration the time value of money in contrast with a simple payback period method. To calculate the discounted payback period, the additional costs of investment in installation of the green roof in comparison to the conventional one, the subsidy program, and the financial benefit in form of annual reduction in cooling energy costs are used.

2 URBAN HEAT ISLAND EFFECT

2.1 Urbanization and climate

Cities occupy a very small proportion of the Earth, but they are the areas of greatest population concentration in the world. The percentage of the population living in cities continues to increase, as the rural population declines. Most of this growth will occur in the economic development area, especially in tropical areas, where urban infrastructure has to be built yet. Thus, in the near future, the largest proportion of humanity will live in places where the local environment has been profoundly modified by the cities, which are already built or will be constructed.

The city centers are characterized by the absence of vegetation and the dominant presence of impermeable surfaces made of asphalt and concrete. The urban climate is a result of heat exchanges between outside surfaces (building surfaces, street surfaces, parks, etc.) and urban atmosphere to produce different microclimates. As detailed in the Literature Review chapter, urbanization has an effect on temperatures in cities. The increased temperature in urban areas also has an impact on other climatologically parameters. Solar radiation is reduced due to scattering and absorption by artificial surfaces. In comparison with the surrounding rural areas, the duration of light in industrial cities is reduced from 10 % to 20 % due to the presence of large buildings. The wind speed is usually reduced, but it could be occasionally increased. Furthermore, it could be changed by the specific roughness of a city and the urban heat island effect (Santamouris, 2001).

2.2 Urban heat island

The urban microclimate is influenced by urban form and their surfaces. Cities are characterized by impervious surfaces with a high concentration of anthropogenic activities leading to significant increases in the air temperatures and the surface temperatures, which are higher than the temperatures of countryside. Such effect is known as the phenomenon "Urban Heat Island" (UHI) (Oke, 1987), which its magnitude depends primarily on the size of the city and local climatic conditions.

In general, Meireles (2011) links the formation of the urban heat island to the following factors:

- Energy transformation within the city, with specific forms, albedo and building materials (thermal properties of the urban construction materials facilitate heat conduction faster than the soil and vegetation in rural areas);
- Reduction of the cooling effects by the decrease of evaporation (few green areas, impervious surfaces, transport of precipitation through the pipe that reduces the amount of water available for evaporation);
- Solar radiation, which is not used for evaporation, is absorbed by streets, buildings, and city air;
- Anthropogenic energy, which is generated by humans and human activity, adds heat to the environment;
- Increased surface roughness (by the presence of buildings of different heights), causes that airflows are disrupted;
- Amount of exposed or covered soil, the condition that elevates the surface temperature;
- City topography, where mountains and valleys can serve as barriers to the dispersion of warm air;
- Thermal properties of buildings and paving materials

Urban heat island is considered as the cumulative effect of all the above-listed factors and defined as the rise in temperature of any anthropogenic area. Such rise in temperature results in a well-defined, distinct "warm island" among the "cool sea" represented by the lower temperature of the area’s nearby natural landscape (Bayindir, 2012), as shown in Figure 1.

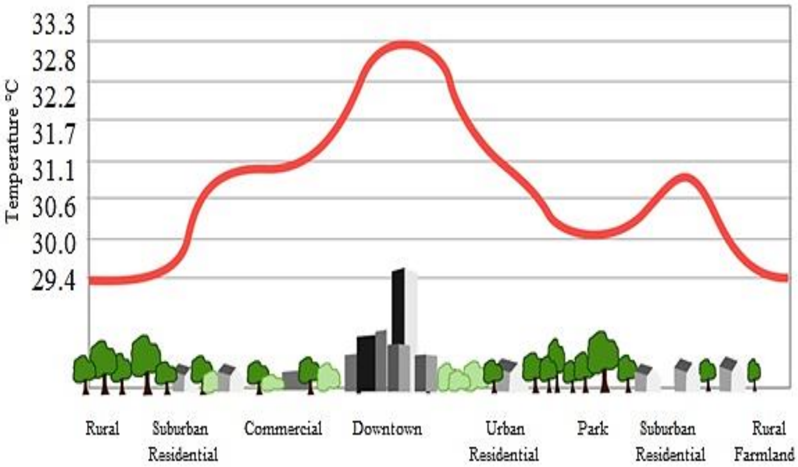

Figure 1: Urban heat island effect
Source: EPA (2008)

As observed in the Figure 1, the urban areas with less vegetation have the higher average temperature in comparison to the periphery. This difference directly affects the quality of life of the population, which lives in these warmer areas of the city. Therefore, it is necessary to preserve and recreate green areas to alleviate this issue.

2.3 Factors influencing urban heat islands

According to Rizwan et al. (2008), urban heat islands are generated by factors that can be categorized as controllable and uncontrollable factors (Figure 2). The controllable factors include anthropogenic heat, air pollutants, sky view factor, green areas, and construction materials. Uncontrollable factors include cloud cover, wind speed, seasons, daylight conditions, and other conditions. It cannot be claimed that one of these factors is more important than the others to formulate the UHI because each city is unique and it always depends on its urban geometry.

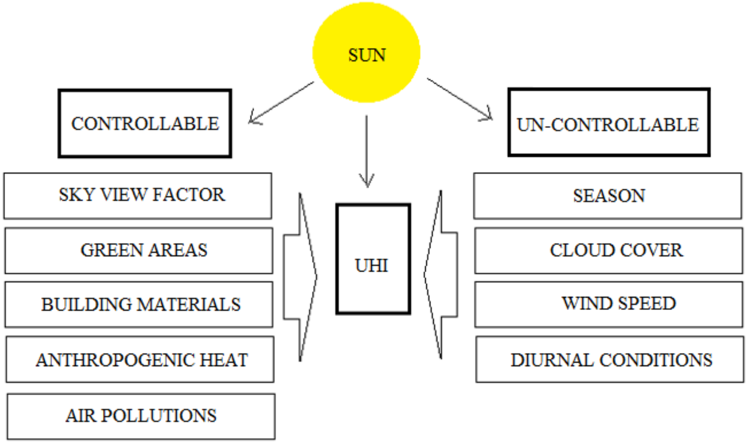

Figure 2: Factors that influence the intensity and formation of urban heat islands
Source: Adapted from Rizwan et al. (2008) by Author

Urban geometry

Urban structures absorb solar radiation or short-wave radiation flux and store heat. After the sun sets, the environment begins to cool and this stored energy is re-radiated as heat or long-wave radiation flux at night. The amount and proportion of the absorbed solar radiation depends on the nature of the underlying surface, color, and geometry. The complex geometry of urban building structures predetermine multiple reflection and absorption of solar radiation resulting in lower albedo values in comparison with the rural areas (Rizwan et al, 2008). Albedo or reflection coefficient is the diffuse reflectivity or reflecting power of a surface. Typically, urban albedo ranging from 0.10 to 0.20 (Figure 3), but in some cities these values can be exceeded. High albedo construction materials reduce the amount of solar radiation absorbed by the building envelope and urban structure and remain their surfaces cooler (Taha, 1997). For example, a white roof reflects most of incoming visible energy from the sun while a black roof absorbs most of the incoming visible energy from the sun. Figure 4 demonstrates how white and black color of roofing material affects the amount of reflected and stored heat of the roof.

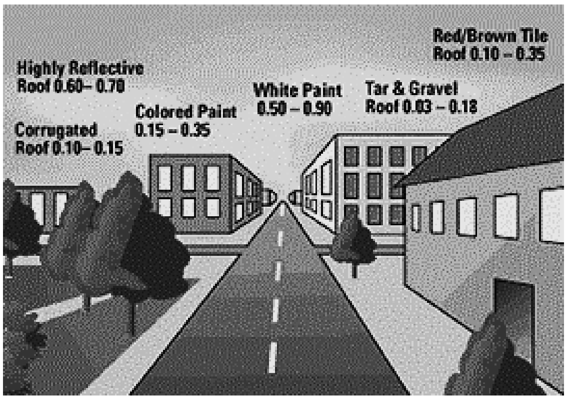

Figure 3: Albedo of different urban surfaces
Source: Kanakiya et al. (2015)

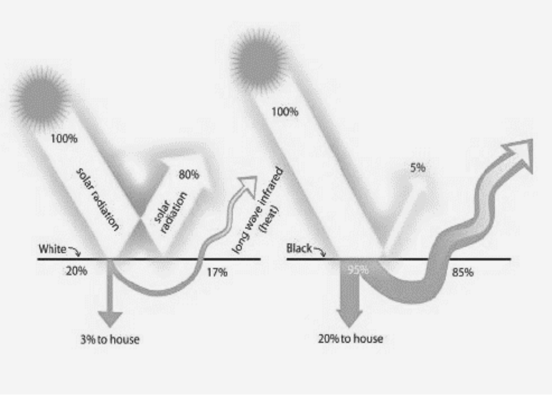

Figure 4: The amount of reflected and stored heat
Source: Howard (2017)

Street geometry and orientation also play an important role in determining the urban heat island. Urban geometry influences the wind flow, radiation and humidity. The factors that play a role in urban geometry are interaction between height-width ratio (H/W) and sky view factor (SVF) in the urban canyon. The ratio between the width of the road and the height of buildings (Figure 5) is fundamental to control heat islands because it influences the process of absorption of solar radiation and long-wave radiation emitted by the surfaces of buildings and soil.

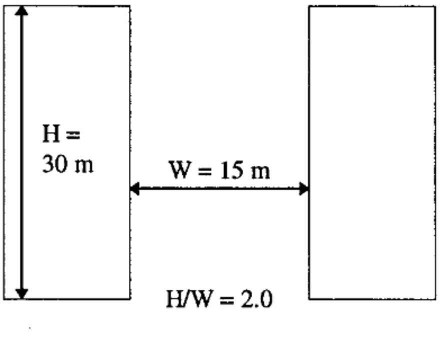

Figure 5: Height-width ratio
Source: Oke (1981)

The layout of buildings and their geometries within an urban area have some influence on the urban canopy heat island. Figure 6 shows the heat island intensity and H/W in study of Oke (1981).

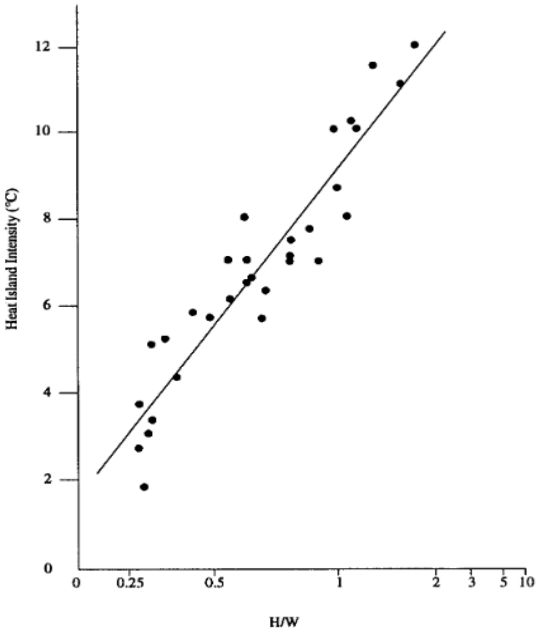

Figure 6: Relationship between heat island intensity and H/W
Source: Oke (1981)

The sky view factor (Figure 7) is defined as dimensionless parameter; it indicates a geometric relationship between the earth and the sky and represents an estimate of the visible area of the sky (Grimmond et al., 2001). Oke (1987) reports in his study that the sky view factor is a major factor causing the phenomenon of heat islands.

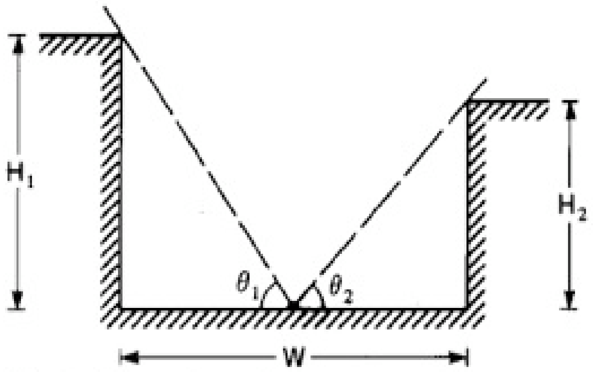

Figure 7: Sky view factor
Source: Oke (1987)

Population density

The factors of population density and size of the city as an indicator of urban heat islands has been studied by Oke (1982), who pointed out that they are correlated (Figure 8). The number of buildings, industrial factories and cars has an effect on population density and city size. Hung et al. (2005) conducted a study of selected tropical cities and discovered the effect of the UHI ranges from 5 to 8 °C in the dry season between 2001 and 2002. This study also highlights that magnitude and extension of urban heat islands have strong correlation to the size of the population of cities. Nowadays, new cities with large populations are characterized by tall buildings which density, the sky view factor, and materials play an important role in the formation of urban heat islands.

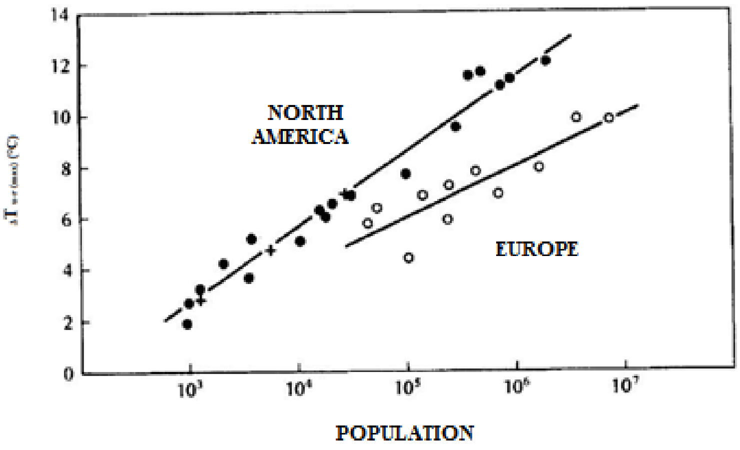

Figure 8: Relation between maximum heat island intensity and population
Source: Oke (1982)

Anthropogenic heat

Anthropogenic heat has been recognized as an important factor affecting the urban heat islands. Anthropogenic heat includes car exhaust heat, industrial heat and heat produced by the activity of people living in an area (air conditioning, etc.). The waste heat increases the atmospheric heat in the city and its surroundings. Kikegawa et al. (2003) found by simulation of urban canopy that the heat waste from air-conditioners cause temperature increases of 1-2 °C in the summer. Ferreira et al. (2010) investigated the anthropogenic heat in Brazilian city Sao Paulo and found that human metabolism is responsible for 9 % of anthropogenic energy, vehicular sources 50 %, and stationary sources, such as air conditioners, are responsible for 41 % of anthropogenic energy.

Vegetation

Another important factor in the creation of heat islands is the loss of vegetation in urban areas. Vegetation and humidity have a significant effect on the microclimate of the urban and rural areas (Figure 9).

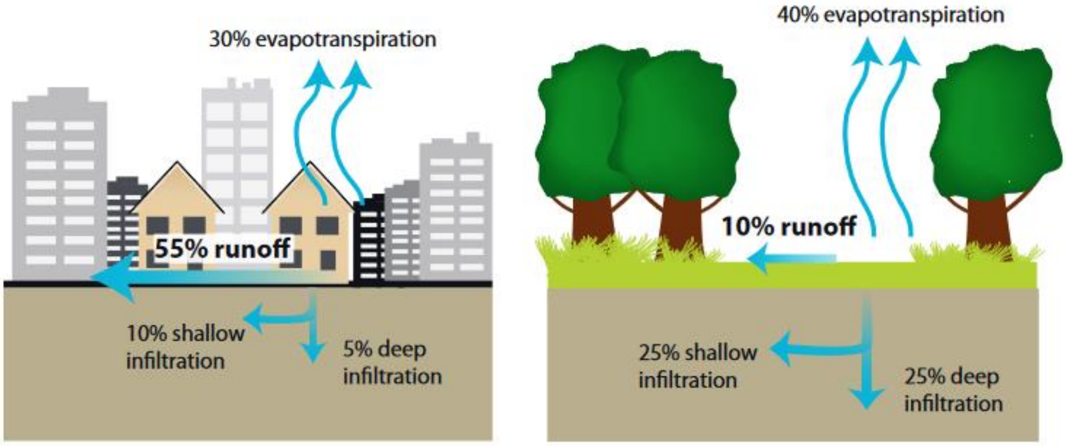

Figure 9: Impervious surfaces and reduced evapotranspiration
Source: EPA (2008)

Non-urban or rural areas are usually covered with vegetation, which helps to maintain the temperature in two important aspects: through the shade and evapotranspiration. Shading reduces the surface temperature by reducing the amount of incoming solar radiation that reaches the surface below the plants. The leaves have a higher reflectance rate compared to man-made surfaces. Only 30 % of the sun's energy reaches the vegetated ground surface, as the rest of the energy is absorbed by the plants and reflected back to the atmosphere (EPA, 2008). Scott et al. (1999) demonstrated that difference in asphalt temperature between shaded and un-shaded area could be up to 20 °C and shaded parking area could reduce internal temperatures of any parked car up to 40 °C. The second way how plants affect the temperature is through the evapotranspiration process. Plants primarily use evapotranspiration to draw water up from the roots to leaves where it is needed for photosynthesis. Evapotranspiration is one of the mechanisms by which plant can a thermally regulate itself by converting water to water vapor dissipating the stored heat in the air (Taha, 1997). Evapotranspiration is also one of the main components in the water cycle affecting the local and regional water balance.

Air pollutants

Rizwan et al. (2008) highlighted that air pollutants, especially mineral dust and aerosols, are responsible for causing urban heat islands through absorption and re-radiating of long wave radiation and inhibition of the corresponding radiative surface cooling producing a pseudo-greenhouse effect, which are responsible for increased temperatures inside cities.

The most electricity is generated by burning fossil fuels such as coal or natural gas, therefore any increase in energy demand can increase air pollution and greenhouse gas emissions. Air pollutants include nitrogen oxides (NO_x), sulfur dioxide (SO_2), particulate matter (PM), carbon monoxide (CO), mercury (Hg) and greenhouse gases including carbon dioxide (CO_2). These air pollutants can have negative effects on human health and contribute to the formation of ground-level ozone (smog), acid rain and heat islands in urban areas.

Time of the day

The heat island is not constant condition, but its intensity varies during the day and is typically stronger during the night, as can be seen in Figure 10.

The increased temperature caused by the UHI effect, which is higher than the average minimum temperature, prevents the body from cooling down at night and poses a risk to public health.

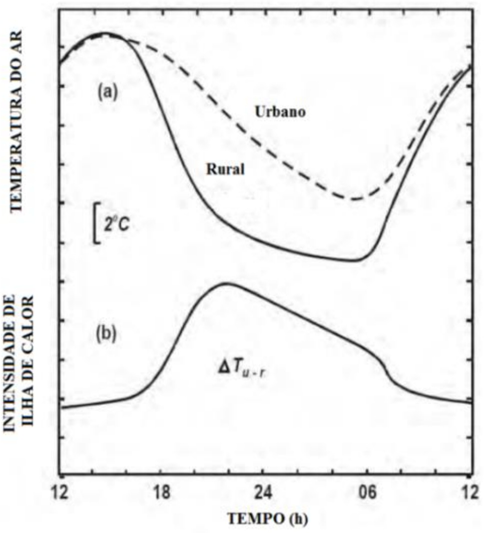

Figure 10: Diurnal UHI cycle with (a) the air temperature (b) the heat island intensity

Source: Oke (1987)

Season

The first factor of uncontrollable factors is season. Intensity of the UHI varies seasonally, and is usually major in summer time, due to changes in the incoming solar radiation and drier weather conditions associated with summer in most regions (Oke, 1987). Different studies pointed out autumn or spring are the second season after summer in heat island intensity. The winter is the time of year, which is characterized as the least intense in formation of heat islands (Oke, 1982).

Wind speed and cloud cover

Urban heat island intensity is often negatively correlated with wind speed and cloud cover. The intensity and occurrence of the UHI is reduced under windy and cloudy conditions when the air is well mixed and local temperature differences are eliminated (Oke, 1982). Clear and calm conditions are ideal for the development of strong heat islands. During cloudless conditions, the radiative cooling in rural areas is often fast, whereas in urban areas, outgoing long-wave radiation is partly trapped in the street canyons. Back-radiation from cloud cover effectively diminishes the radiative cooling both in urban and rural areas, thus limiting the probability of large urban-rural temperature differences (Oke, 1987).

The effect of wind speed is often considered more important than that of cloud cover (Morris et al., 2001). Morris et al. (2001) focused on the influences of cloud cover and wind speed on the nocturnal urban heat island in Melbourne and they discovered that an increase in the amount of cloud cover and wind speed in excess of 2.0 m s^{-1} resulted in a statistically significant (95% confidence level) reduction in magnitude of the UHI. The study also showed that cloud cover was more limiting than wind speed in the UHI development for all seasons except summer.

2.4 Effects of UHI on energy consumption

The urban heat island effect has a large impact on building energy use for heating and cooling because of the change in outdoor conditions. As a result of the UHI effect, energy consumption levels for cooling and heating are expected to increase and decrease. However, this varies in different locations due to their climates.

Earlier studies showed that the heating effect dominates the cooling effect in cold countries such as Sweden, which means that the global warming would result in a decline in electricity demand in these countries. Although, many publications have projected the reverse for Germany with the cooling effect dominating the heating effect (Bessec et al., 2008). The urban heat island effect is likely to significantly increase the energy demand in all regions for space cooling, which is provided almost entirely by electricity. The effect in most studies is non-linear with respect to temperature and humidity, such that the percentage impact increases more than proportionally with increase in temperature (Sailor et al., 2004).

Electricity demand for cooling is predicted to increase by roughly 5 % to 20 % per 1 °C of the temperature increase. This can differ by location and customer class. Mansur et al. (2005) projected that when temperatures were increased by 1 °C, the electricity consumption increased by 5 %, natural gas consumption by 6 %, and fuel oil consumption brought 15 % more electricity. Huang's (2006) predictions show an even stronger growth of electricity consumption of about 38 % increase in 2020 for 1.7 °C increase in temperature and 89 % increase in 2050 for 3.4 °C increase.

Study of Frank (2005), which focused on residential and office building in Switzerland, assume by calculation that 0.7 - 4.4 °C increase in average annual air temperature cause 36 - 58 % decrease in heating demand and 220 - 1050% increase for cooling demand. Asimakopoulos et al. (2012) undertook simulation in TRNSYS for 3 types of building in Greece with climate model data, which took into account climate change estimates for the period 2010 - 2100, to demonstrate 50 % decrease in heating and 248 % increase in cooling demand by 2100.

2.5 Urban heat island effect in Prague

Trend of changes in the Czech Republic takes place in the context of climate changes in Europe. Two major climatological characteristics, which come under ongoing changes in Earth's climate system, are temperature and precipitation that serve as basic indicators of climate change.

The evolution of climate over the last two centuries in Prague can be demonstrated by measurements of meteorological station, which is situated in the Clementinum and has the longest observation in the Czech Republic. Prague Clementinum station is located in the city center, and therefore is affected by the urban heat island effect. Due to growing urbanization of the city, the increase of average annual air temperature can be observed by this meteorological station since 1775 (Figure 11).

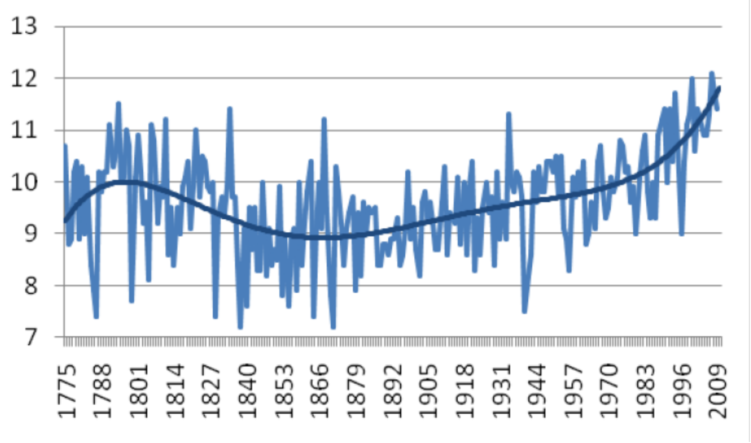

Figure 11: The increase of average annual air temperature (°C) during 1775-2010

Source: CHMU (2012)

The course of the average annual air temperature of the meteorological Clementinum during the period 1775-2009 shows that the end of the 18th century was accompanied by the increase in temperature, which was in the first half of the 19th century replaced by the decline. Since the second half of the 19th century, the temperature gradually increased.

Given the global warming and climate changes, the biggest cities suffer from the urban heat island effect, due to their built-up areas, population density, and lack of green areas (Figure 12 and 13). As can be seen from the Figure 12, Prague (Praha) is affected by excess heat, as well as Vienna (Vídeň) or Munich (Mnichov).

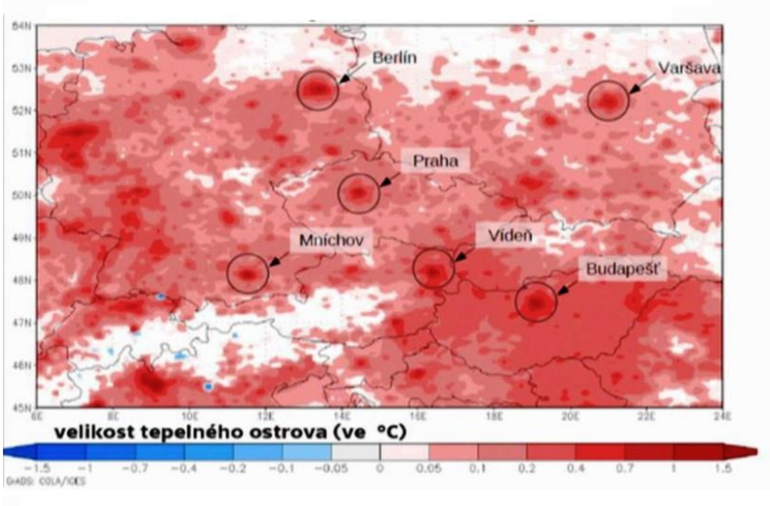

Figure 12: Heat islands in Central Europe

Source: ČT (2014)

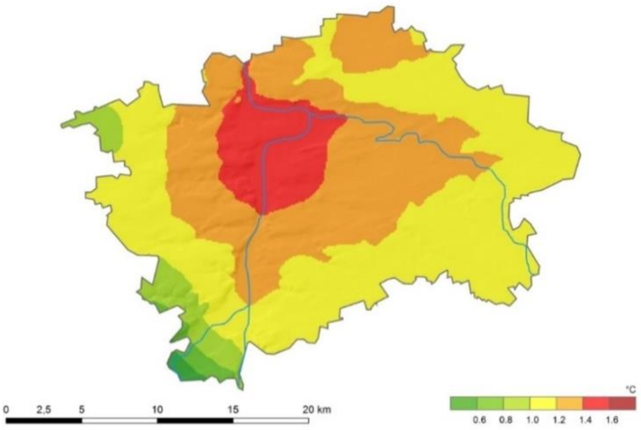

Figure 13: The difference in average daily minimum temperatures in Prague

Source: CHMU

According the Michal Žak from Czech Hydrometeorological Institute: "*in Prague, the average annual temperature is higher by 2.5 °C compared to the surrounding countryside"*. In some cases, the temperature differences may reach up to 10 °C in comparison to suburban and rural areas. Prague got involved in European project called The UHI Project, which is focused on the mitigation of the urban heat island effect. In this project, Prague is very interesting case based on its arterial road, which represents a deep canyon with little vegetation and source of anthropogenic heat from exhaust fumes from cars.

In term of future development, the scientists expect a gradual increase in the average air temperature by 1.5 °C around 2050 and 3.3 °C by the end of this century in the Czech Republic. In recent years, a significant increase in the number of tropical days (i.e. the day when the maximum temperature exceeds 30 °C) was registered and it is expected that this trend will continue in the future. In connection with this, there was also recorded an increase in the number of tropical nights (i.e. the night when the minimum temperature does not drop under 20 °C) and this trend is predicted in the future too. The projection for emission scenario A1B[1] show that the number of tropical days and their extremity will increase in future. It is expected that in the near future (2021-2050) the number of tropical days will increase[2] by 50 % compared to the reference period (1961-2000) (Prazakova, 2016). These heat waves have already a negative impact on human health, economy and may cause frequent fires.

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[1] The Emissions Scenarios of the Special Report on Emissions Scenarios, the three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end-use technologies), (Online Available from: https://www.ipcc.ch/ipccreports/tar/wg1/029.htm#storya1).

2.6 Urban heat island effect in Rio de Janeiro

The metropolitan area of Rio de Janeiro is one of the most urbanized areas of the Brazil with very large population, over 6 million habitants (IBGE, 2010). For this reason, this urban area has a great impact on the increase of urban heat island effect. In Rio de Janeiro, especially in the hottest period of the year, temperature differences reach up to 25 °C and can be observed in comparison with areas with different levels of urbanization. Some layers of heat occur on the surface, while others occur a few meters above the surface. The cities in tropical latitudes, such as Rio de Janeiro, face this effect during the day (Reynolds, 2015).

Filho et al. (2009) emphasize the importance of urban climatology studies in tropical countries. The authors present some results of thermodynamics and urban heat island temporal evolution for the metropolitan area of Rio de Janeiro. Three groups of different microclimates were identified in the metropolitan region of Rio de Janeiro. The UHI behavioral pattern can be determined by the temporal evolution of the differences between the virtual potential temperature in vegetated and urbanized areas, including the effects of humidity on the positive buoyancy of air parcels during the convective period. Another finding by the authors is that the tropical UHI in Rio de Janeiro occurs during the morning and not during the night, as in temperate areas. The urban heat island has a maximum daylight in the morning for all seasons, being more intense along the months in the transition between the rainy summer and dry winter (February - May) with an amplitude of 4 - 5 °C (as opposed to a range of 2 - 3 °C in the other months).

In the study by Sena et al. (2014), the authors observed surface temperature changes over hours in the metropolitan region of Rio de Janeiro (Figure 14 and 15). The satellite image (Figure 15) reveals large heat islands with average continental summer surface temperature around 45 °C at 16h.

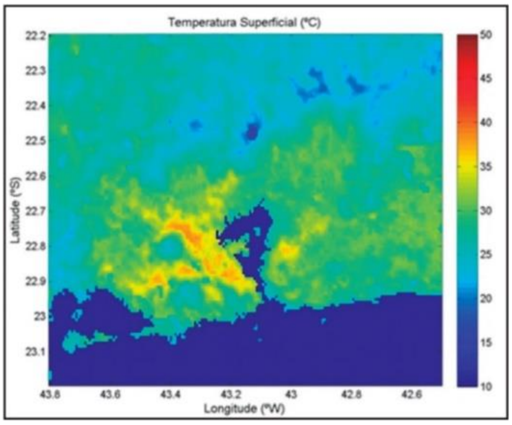

Figure 14: Summer surface temperature at 13h

Source: Sena et. al. (2014)

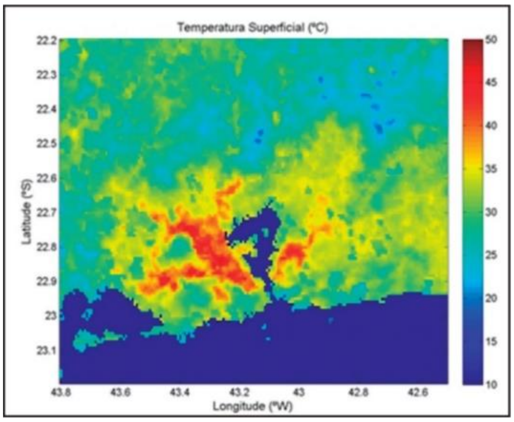

Figure 15: Summer surface temperature at 16h

Source: Sena et. al. (2014)

2.7 Urban heat island effect in Sydney

"The liveability of Australia's cities will be affected by how their sustainability is managed."

(Australian Government, 2013)

Nowadays, over three-quarters of Australians are living in urban areas (Block et. al., 2012) which causing the loss of vegetation within cities leading to the creation of the urban heat island effect. A strong existence of the UHI in Sydney was confirmed by Greening Australia (2007) based on the examined temperature records. The most impacted area is Western Sydney, especially Blacktown, Parramatta, and Richmond suburb, which do not receive the moderating influence of a cooling sea breeze. The climate of these suburbs is also associated with high-density building development. Thus, the UHI has widened the gap between Western Sydney and costal Sydney.

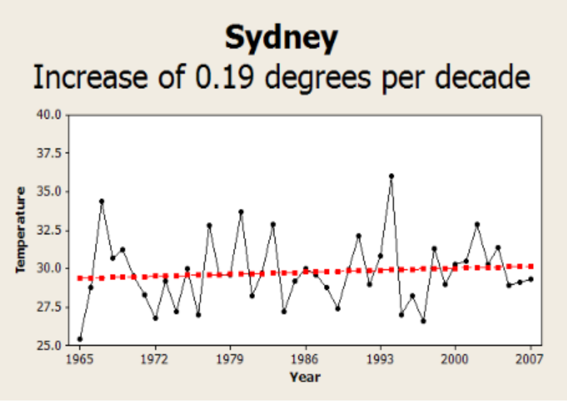

Figure 16: Temperature of a hot January day
Source: Greening Australia (2007)

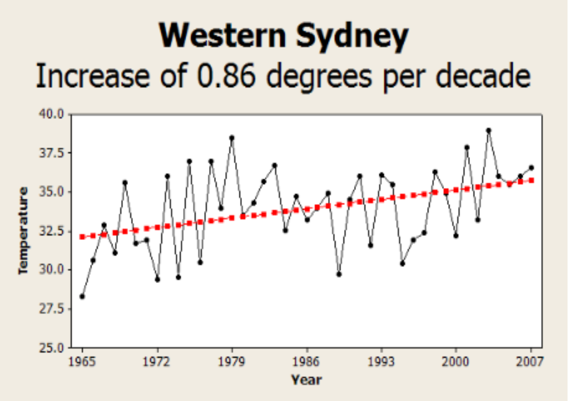

Figure 17: Temperature of a hot January day
Source: Greening Australia (2007)

Over the last 40 years all Western Sydney weather stations have measured an increase in annual average temperatures over and above what would be expected through global warming. Figures 16 and 17 show that the temperatures of a hot day (the highest temperature that occurs three times a month) in Western Sydney have risen dramatically. Osmond and Sharifi (2017) state that maximum summer temperatures can be up to 9 degrees higher in Western Sydney than in Central Sydney. He also claims that the number of days over 35 degrees in Western Sydney has increased by 250 % since 1965 compared with 22 % in Central Sydney.

3 DESCRIPTION OF GREEN ROOFS

Green roof means an extension of an above Grade roof, built on top of a human-made structure, that allows vegetation to grow in a growing medium and which is designed, constructed and maintained.

(City of Toronto By-law No.583-2009 § 492-1 Definitions)

Green roof is a roof of a building that is partially or completely covered with vegetation and a growing medium, planted over a waterproofing membrane protection. It may also include additional layers such as a root barrier and drainage and irrigation systems. The concept of growing vegetation on a rooftop is not an innovation but nowadays is considered as an old solution applied to current problems.

3.1 History of green roofs

From a historical perspective, greenery on green roofs does not represent a new phenomenon. When people left the caves and mountain gorges, which were protecting them from the elements, they began building the first shelters with roofs from branches and wicker. When they built the first huts, they needed to keep themselves warm. Therefore, they sealed roofs with greensward and clay. Airborne seeds sprayed onto roofs, caused the growth of greenery that provided even better thermal insulation. These dwellings can be seen today in every European open-air museum of folk architecture.

The history of green roofs in the world can be divided into two main categories: intensive and extensive. An intensive green roof is typically called "roof garden". It is traditionally more expensive because the soil medium depths are between 1.0 and 1.3 m to enable the growth of small trees and a wide variety of other plants. The first known roof gardens were located on the famous Ziggurats of Mesopotamia between 4 000 – 600 BC. The ziggurats were great stepped pyramid towers of stone, built in stages. At the landings of these stepped towers, plantings of trees and shrubs on flat terraces softened the climb and offered relief from the heat of Babylon (Werthmann, 2007).

The most famous green roofs were the Hanging Gardens of Babylon, built by the Persians around the 500 B.C (Weiler and Barth, 2009), one of the Seven Wonders of the Ancient World.

In the Middle Ages and the Renaissance, the art of building roof gardens started to develop again, especially in Italy. They were established on the roof of the palace of the Medici - Villa Careggi in Florence and Palazzo Picolomini in Pienza. In Russia, they were built as sign of luxury since the end of the Renaissance period. In the US, rooftop gardens became popular at the turn of the 20th century.

Extensive green roofs have a thinner profile that makes them lighter and more economical. They were mainly built in Scandinavia, Canada, Iceland, where these roofs are still a traditional element of modern architecture. In the cold Nordic climates, green roofs are preferred for their good thermal insulation properties. They are also used for the opposite reason, to insulate the interior from the outside heat, and they are utilized in some tropical countries, such as Tanzania (Minke, 2001). While the history of roof gardens can be connected with the cities and especially their affluent residents, extensive green roofs are more of a matter of utility (isolation from the surrounding environment) and are found more often in the countryside or in small towns. There is much less information available about the history of extensive green roofs than there is about the history of intensive green roofs. This is probably related to the fact that while intensive roof gardens were urban affairs and also a showcase of social prestige while extensive green roofs were more of a pragmatic attempt to use nature in the fight against the elements. This may be due to the fact, while the culture of the Mediterranean society was already relatively developed in the antiquity, the northern areas experienced a similar development a while later.

Currently, these differences are not as pronounced. These days, the main difference is in their geographical distribution, which is significantly linked to the climate conditions. In warmer areas (e.g. Mediterranean), there are many houses with roof gardens, in colder regions such as Scandinavia they are logically found very rarely.

The modern history of green roofs

The main pioneers of the modern development of green roofs were German-speaking countries, with Germany at the forefront. In these countries, many scientists have been involved in research of new technologies and the possibility of planting green roofs since the 1960s. These efforts were mostly successful and the number of green roofs has been growing significantly (Dunnett and Kingsbury, 2008). An interesting and well-known example is the famous Hundertwasser in Vienna (Figure 18). The house, which was completed in 1985, stands in the street Löwengasse. There were a total of 992 tons of soil and 250 trees and shrubs transported to the rooftop of the house. Originally, it was meant to serve as an accommodation for socially disadvantaged people, but became a tourist attraction and one of the most famous buildings with a green roof in Austria.

Figure 18: Intensive green roof, Hundertwasserhaus, Vienna, Austria
Source: Author

The World Exhibition in Paris 1867 was one of the first demonstrations of a planted concrete roof in Western Europe, where visitors could have got acquainted with extensive roofs into the mainstream where the showcase of a concrete "nature roof" was displayed (Dunnett and Kingsbury, 2008). The effort to build green roofs due to environmental considerations and to return nature to the life of city dwellers comes only in the 20th century. Perhaps the best-known promoter of this idea was the architect Le Corbusier. Le Corbusier is considered one of the first systematic roof greeners. In his famous Five points of new architecture, written in 1930's, roof gardens came second. After a brief explanation of structural details, Le Corbusier concludes with the words: *"The roof garden becomes the* *favorite place in the house and additionally for the town it means that the built-up space lost is regained."* (Le Corbusier, 1946).

In the first half of the 20th century, the oversized weight was still an obstacle to the greater development of green roofs both for structural elements and soil substrates. The development of industrial chemicals and plastics partially resolved this problem after World War II.

In recent years, many architects have begun to design green roofs in many European and non-European countries. In the traditionally environmentally minded countries such as Germany, Austria, and Switzerland, there is a large boom of green roofs since the 1960s (Čermaková. & Mužiková, 2009). Especially in Germany, many specialized companies were set up, which dealt with the research of green roofs, and primarily their implementation (an example could be ZinCo or Optigrün - Companies based in Stuttgart). In 1989, approximately 100 ha of green roofs were installed (Čermaková. & Mužiková, 2009). The impetus for this was especially strong environmental movement and the effort to return the nature to urban life (Dunnett and Kingsbury, 2008).

Nowadays, the significance and application of green roofs consists in their contribution to the urban landscape. In addition, currently, because of the significant range of construction and the need to protect agricultural land, the use of green roofs is necessary in terms of the economical use of space. Their usage is actually a logical consequence of a lack of space.

3.2 Components of green roofs

Most green roofs have the same basic components; waterproof and root resistant membrane, drainage system, substrate and vegetation layer, which are described in more detail as follows.

Vegetation

This layer is the living component of the green roof system. There are four main methods of establishing vegetation on a green roof:

1. Vegetation Mats present the most expensive way of greening a roof but provide 90 - 100 % vegetation cover when installed.

2. Plug Planting requires planting a pot grown plant directly into the substrate. This method allows for the easy mixing of plant species but takes longer to establish vegetation coverage.
3. Seeds and Cuttings can be hand distributed or sprayed onto a roof in a gel or hydromulch that holds the seeds in place until plants are established. This method is cost effective but is a slow of achieving vegetation cover (Carroll, 2010).
4. Natural Colonization is used to preserve native species. A bare substrate is naturally colonized in sympathy with its local environment. It is the cheapest and most environmentally and ecologically beneficial way of vegetating a green roof.

Growing media

The growing media or soil substrate presents the rooting layer for the plants and is comprised of air, water, organic material, and aggregate materials. The purpose of this layer is to provide nutrients, mechanical strength open pore structure, chemical composition, and drainage properties for plants to survive. The depth of the growing media depends on the type of green roof system.

Drainage layer

The function of the drainage layer is, in combination with growing media, to retain water during dry periods or expel surplus water from the roof during rain periods. The most critical role of the drainage layer is to provide adequate flow of water off the roof during and after a rain event. This is particularly important on flat roof constructions, when stormwater can result in structural fatigue. It is also crucial to design the correct drainage conditions to allow plants to survive and flourish.

Root barrier

The root barrier is an essential part of a green roof system because it protects the waterproofing membrane from root penetration into membrane seams, and harmful effect of the soil microbes acting on the waterproofing layer.

The type of root barrier depends on the system and the type of plants used and is therefore usually specified by the green roof supplier or waterproofing supplier. Commonly, the roof barrier is made of thermoplastic sheets such as PVC, TPO or polyethylene.

Waterproofing membrane

The waterproofing membrane is the system that resists hydrostatic pressure and provides protection against water ingress. There are many types of waterproofing membranes for different types of roof decks and substrates (i.e., steel or concrete decks). Worldwide, polyvinyl chloride (PVC) and polymer modified bituminous membranes are the most common. In some cases, waterproofing membrane may act as a roof barrier.

3.2.1 Types of green roofs

There are several different types of green roof: extensive, semi-intensive and intensive. The main difference between each of these types of green roof is the depth of the substrate and the type of vegetation. The thicker layer of growing media allows a greater variety of plants.

Extensive green roof

An extensive green roof can be considered as an alternative to traditional roof system because of its durability, maximum functionality, and minimal maintenance. This type of green roof can be used on both flat roofs and sloping roofs. It is comprised of a very thin layer of soil (about 100 mm) with a load capacity of about 75 kg/m^2. The main extensive green roof specifications are shown in Table 1. Extensive green roofs are less costly to install than intensive green roofs and are also cheaper to maintain. They are mainly developed for ecological and aesthetic reasons, not for recreational reasons. The plants are chosen for their stress tolerant characteristics (Oberndorfer, 2007). The plants that are typically used include sedums, succulent, grasses, mosses, and wild flowers (Mayor of London, 2008), which require very low maintenance and are able to survive on the shallow low-nutrient growing media. The extensive green roof of the shopping center Novy Smichov, located in the Andel quarter in Prague's bustling 5th district, is an example of an extensive green roof in the Czech Republic (Figure 19).

Figure 19: Extensive green roof of the shopping centre Novy Smichov, Prague

Source: Author

Semi-intensive green roof

Semi-intensive green roofs in terms of requirements fall in between extensive and intensive green roof systems (Table 1). A semi-intensive green roof system is characterized by ground covers, grasses, small herbaceous plants, small shrubs and coppices, requiring moderate maintenance, and occasional irrigation. In comparison to intensive green roofs, the potential for using this type of the roof for amenity purposes is limited based on thinner layer of growing media. This system is able to retain more stormwater than an extensive system and offers the potential to host a richer ecology.

Intensive green roof

Intensive green roofs, which are usually also called roof gardens, require similar management as conventional gardens and parks with almost no limit to the type of available plants ranging from herbaceous plants to small trees (Table 1). This type of green roofs typically has a thick, nutrient rich, growing medium of 300 mm or more, lush growth of vegetation and require more water than an extensive green roof and therefore have an irrigation system (Oberndorfer, 2007). Due to the size of the plants used, the depth of growing media and its high water retention, the weight of intensive green roofs is significantly higher than that of conventional roofs. Therefore, substantial reinforcement of an existing roof structure or the inclusion of additional building structural support is required (Carroll, 2010). Intensive green roofs offer open space for people and for recreational use and also provide great potential for design and biodiversity.

Table 1: Types of green roofs

Criteria	**Extensive green roof**	**Semi-extensive green roof**	**Intensive green roof**
Load-bearing component	Concrete, wood	Concrete	Concrete Maximum pitch 5%
Plant choice	Sedums, mosses, perennials	Perennials, small shrubs, lawns	Shrubs, tree, lawns
Thickness of growing medium	40-150 mm	120-300 mm	300 and over mm
Weight of complete system (kg/m^2)	75 to 180	200 to 500	500 to 2000
Irrigation	No*	Yes	Yes
Maintenance	low	high	very high
Cost of roofing	€	€€€	€€€€
Accessibility	No	Limited	Yes

Source: adapted from Tailor (2010) by Author

3.3 Benefits of green roofs

Green roofs provide several environmental, economic, and social benefits for the individual building and the wider urban environment and can positively contribute towards issues such as biodiversity, flood prevention, climate change mitigation, and increasing green space in urban areas. The focus of this thesis is on the evaluation of the role in mitigating the urban heat island effect. However, additional benefits range from reduction of energy use and CO_2 emissions, stormwater management impacts on local infrastructure, reduction of pollution levels in the air to amenity benefits for building occupants and the community.

Mitigation of urban heat island effect

A range of factors influence how urban surfaces interact with the atmosphere including: moisture available for evapotranspiration, anthropogenic heating, and albedo (Dousset and Gourmelon 2003). Most urban areas have higher air temperatures, on average 2 °C higher, than their rural areas (Taha 1997). Akbari et al. (2001) claim that the peak summertime temperatures are as much as 2.5 °C higher in a typical city than in surrounding rural counterparts.

Many studies established the correlation between an increase in green areas and a reduction in local temperature (Takebayashi and Moriyama, 2007), recommending the augmentation of urban green areas as a possible mitigation strategy for the urban heat islands. Given densely urbanized areas, there are few spaces that can be converted into green areas, and therefore one of the possibilities is to turn conventional black roofs into green ones.

Reintroducing vegetation on roofs is one of the most promising solutions to the problem of urban heat islands. Green roofs reduce summer air temperatures GSA (2011) green roofs can influence heat islands in the following ways:

- By cooling buildings through the natural processes of plant (physical act of shading, photosynthesis and evapotranspiration);
- By increasing the amount of solar energy that is reflected rather than absorbed;
- By warming up more slowly in sunlight than conventional roofs.

Green roofs have the same energy providers as conventional roofs, but they have additional energy consumers of shading, photosynthesis and evapotranspiration that set it apart as a living system (Mayor of London, 2008). By shading, the plants and growing media of green roof block sunlight from reaching the underlying roof membrane and reduce the surface temperature below the plants. Following this, these cooler surfaces reduce the sensible heat re-emitted into the atmosphere (EPA, 2008). In the summer, 70 to 90 % of the sunlight is absorbed by green plants and converted thought photosynthesis into organic matter and the rest of the sunlight is reflected back into the atmosphere. Evapotranspiration is the sum of the processes plant transpiration and evaporation (Figure 20). The transpiration is the process of the water movement though the roots of plants and emitted through the leaves. This process is triggered by the sunrise because light has a controlling effect on the opening of the stoma through which water primarily escapes in gaseous state. The evaporation is a process when the surface of vegetation and the surrounding growing medium convert water from liquid to gas. Both these processes cool the air by using heat to evaporate water (EPA, 2008).

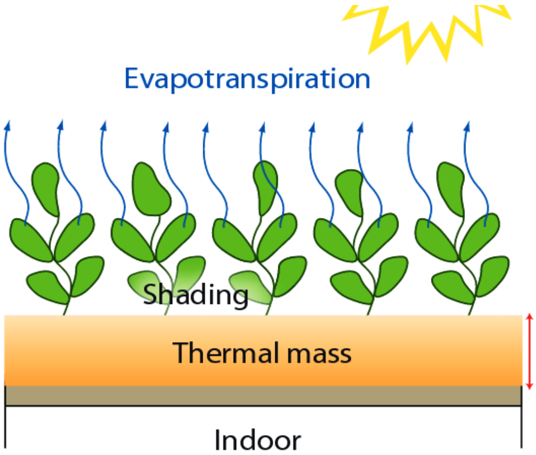

Figure 20: Evapotranspiration and shading on a green roof

Source: EPA (2008)

The quantification of the evapotranspiration is quite complicated. Therefore, effects of vegetation on convective thermal flow, evapotranspiration through soil and vegetation, heat transfer through the ground with change in soil thermo-physical properties and moisture have to be considered. In the following equations, the energy balances for vegetation (Eq. 1) and ground (Eq. 2) are reported.

$$F_f = \sigma \left[I_s^{\downarrow}(1-\alpha) + \varepsilon_f I_{ir}^{\downarrow} - \varepsilon_f \alpha T_f^4 - P_f\right] + \frac{\varepsilon_f \varepsilon_g \sigma}{\varepsilon_1}\left(T_g^4 - T_f^4\right) + H_f + L_f \qquad (1)$$

where

σ = Stefan-Boltzman constant (5.699×10^{-8} W/m^2 ·K^4)

$I_S^{\downarrow}$ = total incoming solar radiation (W/m^2)

ε_f = air emissivity

$I_{ir}^{\downarrow}$ = total incoming infrared radiation (W/m^2)

α = surface albedo

T_f = air temperature (K)

P_f = precipitation heat at the atmosphere/foliage interface (W/m^2)

ε_g = ground emissivity

ε_1 = emissivity (0.8 at a rate of 800 W/m^2)

T_g = ground temperature (K)

H_f = sensible heat at the atmosphere/foliage interface (W/m^2)

L_f = latent heat at the atmosphere/foliage interface (W/m^2)

$$F_g = (1-\sigma)\ \left[I_s^{\downarrow}(1-\alpha) + \varepsilon_g I_{ir}^{\downarrow} - \varepsilon_g \alpha T_g^4\right] + \frac{\varepsilon_f \varepsilon_g \sigma}{\varepsilon_1}\left(T_g^4 - T_f^4\right) + H_g + L_g + \kappa \frac{\delta T_g}{\delta Z} \qquad (2)$$

where

H_g = sensible heat at the foliage/ground interface (W/m^2)

L_g = latent heat at the foliage/ground interface (W/m^2)

P_g = precipitation heat at the foliage/ground interface (W/m^2)

Z = depth into the soil and

κ = thermal conductivity

Eq. 1 takes into account the part of solar radiation absorbed by the vegetation. The sensible (H_f) and latent (L_f) thermal flows are described by Frankestein and Koenig (2004) and reported (Sailor, 2008). The term ‘‘LAI’’ (leaf area index, m^2/m^2) identifies the ‘‘foliage’s area’’ to ‘‘roof area’’ ratio. Eq. 2, as cited, evaluates the energy balances in the soil.

Other factor, which influences heat islands, is albedo[3]. Dark materials have low albedo values, which causing high absorption of sunlight. For example, in case of asphalt, which albedo is around 0.05 - 0.20, 80 to 95 % of solar radiation is absorbed and transformed into heat energy. Materials that have high albedo values are cooler in summer because they reflect more energy from the sun than materials with low albedo value. It is claimed by GSA (2011) that the reduction of the urban heat island by green roofs does not depend on albedo, but on transformation of the absorbed sunlight into water vapor through evapotranspiration. Though evapotranspiration, plants can use up to half the solar energy that hits a surface to convert liquid water in their leaves into water vapor they release to the atmosphere.

Gaffin (2005) reported that green roofs could cool as effectively as the brightest white roofs. Albedo of green roof is between 0.25 and 0.30, but taking into consideration evapotranspiration, the value of "equivalent albedo" is generally around 0.70 to 0.85.

The thesis, which was conducted by Konášová (2016) at UFRJ, shows the role of green roof as migration strategy of urban heat islands in Rio de Janeiro. The measurements of meteorological weather stations demonstrate that the average air temperature 1.5m above the green roof was 24.19 °C and above the flat reinforced concrete slab was 24.84 °C during observed period from February 2016 to November 2016. The biggest difference in

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[3] Albedo is the "whiteness" of a surface. Its dimensionless nature lets it be expressed as a percentage and is measured on a scale from zero (no reflection) of a perfectly black surface to 1 for perfect reflection of a white surface (Wikipedia, 2017. Online available from: https://en.wikipedia.org/wiki/Albedo)

the average air temperature was 1.24 °C in February and the lowest was 0.19 °C in June. The observation from graphs points out that the green roof decreases the heat waves both during daytime and nighttime, thus creates better conditions for sleep thanks to its thermal characteristics.

There is some disagreement about which of these factors has the most beneficial role in mitigating the UHI. It is reported by Niachou et al. (2001) that the main factor is protection from solar radiation or shading in other words. However, a simulation conducted by Solecki, et al. (2005) suggests that the direct effect of shading is secondary to the indirect effect of evapotranspiration.

Other site-specific factors such as roof's composition, geographic location, solar exposure, roof composition, and moisture content of the growing medium influence green roof temperatures (EPA, 2008).

The project, which was undertook in Slavkov u Brna by LIKO-S Company, focused on an effectiveness of green roofs in decreasing the surface temperature and influencing indoor microclimate. The investigated conventional roof, which is surrounded by lake, was divided into three parts. First part is bare roof with waterproofing protection, second one is additionally with gravel layer, and last one with vegetation layer. The Figure 21 shows thermography imagines of examined roof that was taken from a drone during the summer day. As can be seen, the difference in the surface temperature between waterproofing layer and vegetation cover was 23 °C. These results confirm that green roof plays a crucial role as UHI mitigation strategy.

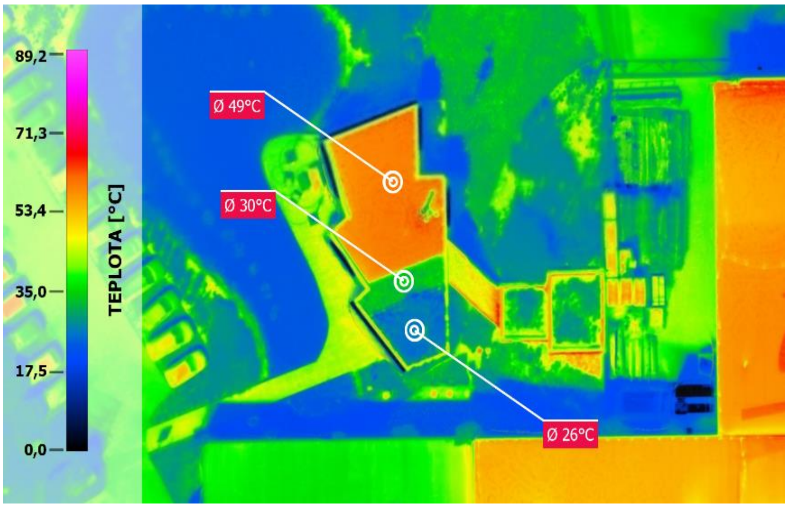


Figure 21: Waterproofing layer of 49°C, gravel layer of 30°C and vegetation cover of 26°C

Source: LIKO-S Company (2016)

Only a few studies aiming to evaluate possible impacts of green roofs on urban heat island effect on the precinct scale are available. One of the examples is a technical report by the Mayor of London (2008), it was estimated that an average of 32 % of roof space in central London, UK could be potentially converted to green roofs. This would lead to an overall energy saving of 19 200 MWh per year or the equivalent of 8 256 CO_2 e tones, the capacity to store 80 000 m^3 of rainwater at roof level, it would provide 256 hectares of habitat, and create 64 hectares of green amenity space. This technical report does not quantify the thermal benefits of green roofs but in comparison with other studies, there are strong indications that this amount of green roof space would have significant effect on mitigation of urban heat islands. Other study conducted in UK by Gill et al. (2007) shows that an increase by 10 % of the urban green in Manchester could amortize the predicted increase by 7 °C or 8.2 °C of the ambient temperature over the next 80 years.

The mitigation potential of green roofs in Singapore was evaluated by study of Wong et al. (2003). The study claimed that the cooling effect of the green roof is restricted by distance from the roof. They found that the reduction of the maximum surface temperature measured under vegetation was about 30 °C. The maximum temperature difference of the ambient air was 4.2 °C around 18:00. The study also concludes that green roofs may be effective when the building height is lower than 10 m. A similar experimental study was carried out by Sun et al. (2012), authors measured the ambient temperature over a green roof and a height of 2.5 m in Taipei. The results of this research shows that green roofs decreased the ambient air temperature by 0.26 °C in average, while the maximum temperature decrease was 1.6 °C.

In New York City, heat island mitigation strategies were evaluated by Rosenzweig et al. (2006). They pointed out that vegetation had the greatest impact on surface temperature, based on the latent heat lost, rather than urban geometry or albedo. The study also cited the work of Bass (2003), which conducted a green roof simulation for Toronto. The simulation found that converting 50 % roof covers within the metropolitan area of Toronto into green ones, an average reduction of city’s summertime heat island of 2 - 3 °C by 0.1 - 0.8 °C in surface temperature could be achieved.

In 2008, Chicago was a leading city in green roofs technology with more than 50 000 m^2 installed vegetative roofs. Smith and Roeber (2011) conducted a simulation study of green roofs to mitigate the UHI in this city by using an equivalent albedo of 0.8 based on the research of Rosenzweig et al. (2006). Due to this simulation, widespread adoption of green roofs, through increased albedo and evapotranspiration, reduces temperatures in the urban environment by as much as 3 °C, for this reason, the usage of vegetative rooftops provides an important cooling effect to the city.

According to the study of Morau et al. (2014), which simulated the dynamic behavior in tropical wet climate, the effectiveness of thermal insulation by green roofs depends on type of plants and their leaf area index and it can reduce temperature in the building between 5 °C and 7 °C. These results confirm that the influence of the green roof on the thermal performance of a building is much better than then other types of traditional roofs in tropical climate conditions.

Akbari et al. (2001) reported that peak urban electric demands increase by 2 - 4 % for every rise of 1 °C in daily maximum air temperature above a threshold of 15 - 20 °C. Based on these results, they highlighted that urban heat islands are responsible for billions of dollars due to an increase of national energy use of air conditioning units by 20 %.

The urban heat island effect causes an increase of the air temperature in built-up areas and large cities, especially tropical ones, which become very hot during the day. Moreover, roofs and pavements typically constitute over 60 % of urban surfaces (roof 20 % and pavements 40 %). Materials of these urban surfaces release their heat slowly during the night, which leads to hot conditions during both the day and night (Akbari et al., 2009).

Several authors have shown that vegetation and permeable surfaces, as is the case of green roofs, can play an important role in mitigating the urban heat island effect, providing greater energy efficiency for the building leading to both significant energy reduction and cost savings. Nevertheless, there is a lack of research, which focuses on green roofs as on the tool mitigating UHI and at the same time reducing energy consumption in urban areas.

Energy savings

The energy savings of green roofs depend on various factors such as climate, type of green roof, specific components of roof, type of building, hourly temperature changes, and the season. In the summer, vegetated roofs have a higher rate of evapotranspiration which creates a cooling effect on and around buildings, thus the heat islands and energy demand are reduced in comparison to conventional ones. It takes longer to heat up green roof that conventional one because of its higher heat capacity. Based on study of GSA (2011) heat flux, or the transfer of heat into or out of a building thought the roof, can be reduces by as much as 72 % compared to black roofs. In the winter, green roofs provide insulation to buildings via their layers, thus reducing peak heating demand. In comparison to hot season, this makes a smaller contribution to energy savings.

The study of Ascione et al. (2013), conducted through the dynamic energy simulation in order to predict energy performances of buildings, shows that green roofs are useful for reducing the energy demand for the cooling space in warm climates, with annual reduction of the primary energy request between 1 % and 11 % for Tenerife, 0 % and 11 % for Sevilla, 2 % and 8 % for Rome. Furthermore, the study also points out that green roofs are suitable for reducing the energy demands for the winter heating need. Annual savings range between 4 % and 7 % for Amsterdam and London, 1 % and 6 % for Oslo.

Nichaou et al. (2001) simulated heating and cooling needs of buildings with green roofs regardless whether the roof was insulated or not in Athens. The greatest savings was calculated by usage of a non-insulated roof with energy savings of 31 to 44 %, for a moderately insulated roof ranged from 3 to 7 %, and finally for a well-insulated roof almost 2 %. By using an infrared thermometer, it was confirmed that the indoor thermal comfort conditions with a green roof were improved by 2 °C.

Report of the Department of Environment of Chicago (2007) estimated that its green roof project could achieve energy savings of approximately 9,270 kWh per year for space cooling and 16,872 kWh per year for space heating. This represents an annual building-level energy savings of about $ 3,600.

Another study, conducted in Toronto on a building with green roof of 2 980 m^2, showed a reduction of approximately 10 % of energy consumed by cooling and heating, which represents a saving of 21,000kWh per year (Bass and Baskaran, 2003).

Air quality

Greenhouse gases are gases that trap heat in the atmosphere. A major greenhouse gas, carbon dioxide (CO_2), is emitted to the atmosphere through natural and anthropogenic processes. The plants on the roofs, as well as also other plants, produce oxygen and consume carbon dioxide due to photosynthesis. They also filter out dust and dirt contained in the air. The particles are collected on the surface of leaves and then rain flushes them to the ground. Plants remove gaseous pollutants by absorbing them through the pores on the surface of a leaf. There are a few studies demonstrating that green roof vegetation can significantly reduce air pollution. One of the examples is study of Yok and Sia (2005) that found 37 % reduction in sulfur dioxide and a 21 % reduction in nitrous acid in the air above a green roof compared to other air samples taken nearby. Others study estimated that 1.0 m^2 of green roof can absorb about 0.2 kg of dust particles and other pollutants per year (Peck and Kuhn, 2003). A green roof's ability to mitigate air pollution depends on the type of vegetation and the surrounding environment.

Yang et al. (2008) reported that a total of 1,675 kg of air pollutants was removed by 19.8 ha of green roofs in one year in Chicago by usage of a dry deposition model. Of this total, O_3 accounted for 52 %, NO_2 for 27 %, PM10 for 14 % and SO_2 for 7 %. The study also showed that the pollutants removed would increase by 2,047 metric tons if all rooftops in Chicago were covered with intensive green roofs.

Stormwater management

One of the other benefits of green roofs is a control over rainwater runoff and retention. The increased urbanization of cities has resulted in less green space and more impervious surfaces. Precipitation generally runs off the roofs of buildings into the gutters and flows into a sewer, but stormwater can lead to flash flooding and reduced water quality though combined sewage overflows into lakes and rivers. Green roofs can prevent this problem by retaining water in the plants and growing media, thus slowing and reducing the amount of stormwater. Therefore, it is necessary to pay attention to the vegetation layers of green roofs in general and not to concentrate only on individual segments.

During rain and immediately after it, a large part of the water evaporates and returns to the atmosphere. Green roof can delay runoff between 95 min (Liu, 2003) and 4 h (Moran et al., 2004), compared with the reference roofs for which runoff was nearly instantaneous. Liu (2003) found that the actual precipitation with intensity of 2.8 mm/h was reduced by the usage of a green roof to a runoff with intensity of 0.5 mm/h.

Fioretti (2010) observed a delay of water runoff from the roof ranging from 71 min to 306 min by analyzing the effect of a Mediterranean climate on a green roof installed on one of the buildings at the University of Genoa in Italy. The obtained results demonstrating a strong dependence of green roof retentiveness on the duration of the dry period preceding the occurrence of precipitation. When the period was shorter than 96 h, the retention capacity was less than 20 %, while for rainfalls separated by less than 12 h, the precipitation water runoff was close to zero.

Baldessar (2012) evaluated the behavior of an extensive green roof with Brazilian native vegetation and its real contribution to minimizing the negative effects of floods. The results of daily measurement simulated in software GreenRoof pointed out benefit of using green roof as a tool of stormwater management process, showing that green roof was able to retain 30.7 % of the precipitated water.

Data collected by researchers Rosenzweig et al. (2006) at Center for Green Roof Research at Columbia University showed that the green roof can capture up to 80 % of rainfall and the conventional roof is able to retain only 24 % of rainfall (Table 2).

Table 2: Average water retention for a traditional roof vs. a green roof

Water Retention for Traditional Roof vs. Green Roof		
Rainfall Retained %	Standard Roof	Green Roof
Average Retention	24 %	80 %
Retention at Peak Runoff	26 %	74 %

Source: Rosenzweig et al. (2006)

Urban biodiversity

Diversity of animal species and vegetation can make an ecosystem more resilient. Green roofs can encourage biodiversity by providing new habitat for wildlife, mainly for plants, microorganisms, insects, and birds in urban areas (Davies et al., 2017). Particularly, blooming roofs are an attraction not only for butterflies, but also bees and other insects. A biodiversity study of seventeen green roofs in Basel, Switzerland found 78 spider and 254 beetle species and 8 % of these spiders and 11 % of beetles were listed as rare and some were considered to be endangered (Brenneisen, 2003). In the UK, green roofs have been found as a habitat for the Black Redstarts, which belong to one of endangered bird species (Gedge, 2003). Water surfaces on the roofs also attract many animals, such as birds, for which the water area serves as a drinking fountain and a space for cooling.

The type of plants and depth of growing media are the two most important factors in encouraging biodiversity on vegetative roofs. Studies suggest that the topography, plant composition, local landscape, and age of a green roof can likewise affect a roof’s ability to enhance biodiversity.

3.4 Green building certifications

Green building certification is an increasingly popular way of demonstrating that the building meets strict requirements in term of sustainability and quality of materials. The certification ensures that the building is environmentally friendly, provides a good indoor environment, has lower operating costs, and delivery innovations.

Thanks to many positive benefits of green roofs for the building and the surrounding area, the green roof helps in obtaining additional credits in case of LEED, BREEAM and SBToolCT certification system.

LEED

Green roof can help to earn credits to achieve LEED certification for the building. Every green roof is unique, thus amount of credits varies based on the project. Points can be obtained from these categories (GRT, 2018):

Sustainable Sites

SS Credit 5.1 – Site Development – Protect or Restore Habitat (1 point)

SS Credit 5.2 – Site Development – Maximize Open Space (1 point)

SS Credit 6.1 – Storm Water Design: Quantity Control (1 point)

SS Credit 7.2 – Heat Island Effect: Roof (1 point)

Water Efficiency

WE Credit 1 –Water Efficient Landscaping (Potential: 2-4 Points)

Energy and Optimization

EA Prerequisite 2: Minimum Energy Performance (Required)

EA Credit 1 – Optimize Energy Performance (Potential: Up to 19 Points)

Materials and Resources

MR Credit 3 – Material Reuse (Potential: 1-2 Points)

MR Credit 4 – Recycled Content (Potential: 1-2 Points)

MR Credit 5.1 – Regional Material (Potential: 1-2 points)

BREEAM

BREEAM certification evaluates the total environmental impact of an individual building development. Green roof has the potential to gain credits within the following BREEAM sections (Hartwell, 2011):

Health and Wellbeing

Hea05 Acoustic performance (Potential: 1 Point) – to mitigate the rainfall noise

Land Use & Ecology

LE03 Mitigating ecological impact (Potential: 2 Points) – to create new habitat

LE04 Enhancing site ecology (Potential: 2 Points) – to plant new species

Management

Man04 Stakeholder participation (Potential: 1 Point) – to bring amenity land to a project

Energy

Ene01 Reduction of CO2 emissions (Potential: Up to 15 Points)

Ene04 Low and zero carbon technologies (Potential: 1 Point) – due to evapotranspiration

Materials

Mat03 Responsible sourcing (Potential: Up to 3 Points)

Mat04 Insulation (Potential: Up to 2 Points) – to improve thermal performance of roof

Waste

Wst01 Construction waste management (Potential: 1 Point) – to minimize waste

Wst02 Recycled aggregates (Potential: 1 Point)

Land Use & Ecology

LE05 Long term impact on biodiversity (Potential: 1 Point) – to create new habitat

Pollution

Pol03 Surface water run-off (Potential: 2 Points) – to retain rainwater

Pol05 Noise attenuation (Potential: 1 Point)

SBToolCZ

SBToolCZ is a Czech national certification tool for evaluating the level of building quality, in accordance with the principles of sustainable construction. By installation of green roof, it is possible to obtain points in this category (Vonka et al., 2011):

Environmental criteria

E.07 Use of greenery on the buildings and allotments

- K2 greenery on the roofs (max 10 points)

3.5 Costs analysis of green roofs

In cost analysis calculated by Konášová (2017) material, labor and transportation costs of green roof are compared to conventional roof (single-ply roof system). The identical family house with a flat roof area of 100 m^2 was used for all roofing systems. The costs of roofs were obtained by price quotations from various contractors from the Czech Republic, Brazil and Australia. The price quotations were valid for year 2017.

Single-ply roofing system of asphalt and gravel

The first system chosen for comparison is the single-ply roofing system of asphalt and gravel. The technical specification of single-ply roofing system is presented in Figure 22. The costs of this roof system are shown in Figure 23.

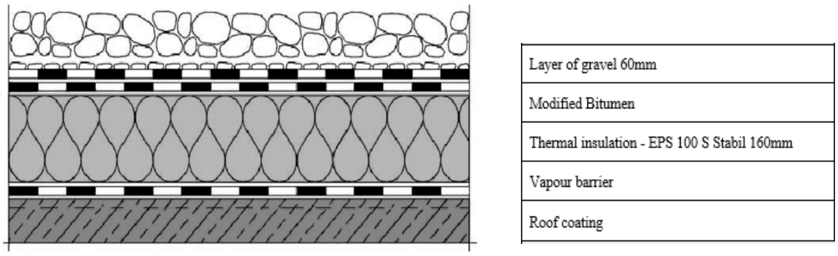


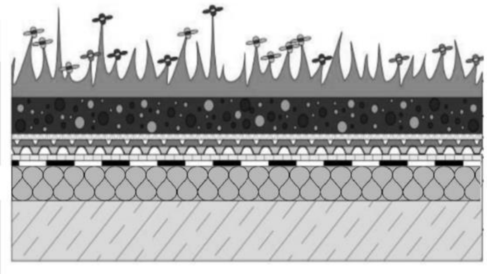
Figure 22: Technical specifications of single-ply roofing system, Source: Konášová (2017)

Single-Ply Roofing System of Asphalt and Gravel	Quantity	Unit	**Unit Cost [€]**			**Total Cost [€]**		
			Czech Rep.	Brazil	Australia	Czech Rep.	Brazil	Australia
Material								
Roof coating	0,01	t	1507,69	1234,62	1830,77	15,08	12,35	18,31
Vapour barrier	115	m²	0,85	0,88	0,49	97,31	101,11	56,39
Thermal insulation EPS 160mm	105	m²	15,19	16,78	19,38	1595,19	1761,58	2034,90
Modified Bitumen	115	m²	4,83	3,12	4,28	555,10	358,27	492,51
Layer of gravel 60mm	4	t	17,69	15,00	22,56	70,77	60,00	90,23
Total material						**2 333,44**	**2 293,30**	**2 692,34**
Labor								
Roof coating implementation	100	m²	0,29	0,54	0,69	28,85	54,23	68,65
Lay vapour barrier	100	m²	1,35	0,60	1,86	134,62	59,54	186,35
Installation of insulation	100	m²	0,98	1,26	2,13	98,08	125,77	212,50
Lay modified bitumen	100	m²	2,15	1,43	2,75	215,38	143,08	274,62
Lay gravel	100	m²	0,04	0,12	0,36	3,54	11,54	35,96
Total labor						**480,46**	**394,15**	**778,08**
Transportation								
Transportation 25km	25	km	9,23	10,25	14,25	230,77	256,15	356,35
Vertical transportation	1	unit	123,08	120,00	150,38	123,08	120,00	150,38
Total transportation						**353,85**	**376,15**	**506,73**
Total costs					**Σ**	**3 167,75**	**3 063,61**	**3 977,15**
Costs per 1 m²						**31,68**	**30,64**	**39,77**

Figure 23: Costs of single-ply roofing system, Source: Konášová (2017)

Green roof

Figure 24 presents technical specifications of green roof system. Based on this technical specification, contractors specialized in installation of green roofs sent their price quotations in order to demonstrate the costs of this roofing system (Figure 25).



Pre-cultivated Sedum Vegetation
Substrate Type E (80mm)
Filter Fleece Type 105
Drainage Board Type FKD 25 (25mm)
Protection and Storage Fleece Type RMS 300
Waterproofing Membrane
Thermal Insulation - EPS 100 S (140mm)

Figure 24: Technical specifications of extensive green roof system, Source: Konášová (2017)

Green roof	Quantity	Unit	**Unit Cost [€]**			**Total Cost [€]**		
			Czech Rep.	Brazil	Australia	Czech Rep.	Brazil	Australia
Material								
Waterproofing membrane	115	m^2	8,35	5,54	11,25	959,81	636,92	1293,31
Protection and storage fleece	115	m^2	1,19	1,15	1,63	137,12	132,69	187,98
Drainage board (25 mm)	105	m^2	6,15	9,28	8,99	646,15	974,08	943,99
Filter fleece	110	m^2	0,98	1,20	1,48	107,88	132,00	163,27
Extensive substrate (80 mm)	8	m^3	71,15	49,38	63,10	569,23	395,08	504,77
Pre-cultivated vegetation 4-5 variations of sedum	10	kg	10,77	17,31	20,07	107,69	173,08	200,73
Thermal insulation EPS 140mm	105	m^2	13,77	15,85	16,56	1445,77	1664,65	1738,32
Total material						**3 973,65**	**4 108,50**	**5 032,36**
Labor								
Roof cleaning	100	m^2	0,19	0,15	0,33	19,23	15,46	32,69
Lay waterproofing membrane	100	m^2	0,38	0,32	0,82	38,46	32,31	81,73
Lay protection and storage fleece	100	m^2	0,38	0,18	0,72	38,46	18,46	71,92
Installation of drainage board	100	m^2	0,58	0,46	1,52	57,69	46,15	151,69
Lay filter fleece	100	m^2	0,38	0,16	0,78	38,46	16,15	78,46
Lay extensive substrate	8	m^3	32,69	24,23	37,27	261,54	193,85	298,15
Planting of pre-cultivated sedum vegetation	100	m^3	1,92	2,77	3,27	192,31	276,92	326,92
Installation of insulation	100	m^2	0,94	1,21	2,04	94,23	121,15	204,00
Total labor						**740,38**	**720,46**	**1 245,58**
Transportation								
Transportation 25km	25	km	11,54	9,44	16,35	288,46	235,96	408,65
Vertical transportation	1	unit	153,85	126,92	196,15	153,85	126,92	196,15
Total transportation						**442,31**	**362,88**	**604,81**
Total costs					**Σ**	**5 156,35**	**5 191,85**	**6 882,74**
Costs per 1 m^2						**51,56**	**51,92**	**68,83**

Figure 25: Costs of green roof system, Source: Konášová (2017)

This analysis gives a financial overview of the green roofs as an alternative option for roofing systems.

3.6 Cost-benefits analysis of green roofs

Costs and benefits of green roofs differ depending on many characteristics such as: type of green roof, location of building, weather conditions, cost of materials, energy consumption, labour, discount rate, and inflation. Konášová (2018) conducted an analysis for two main types of green roofs: extensive and intensive. Costs and benefits are divided in two categories: personal and social. Personal costs and benefits of green roofs are those that are achieved just by the property owner. Social costs and benefits are those achieved by society. Analysis estimates and totals up the equivalent money value of the benefits and costs of vegetated roofs to establish whether their installation is worth it.

Table 3: Private and Social costs and benefits of green roofs

Costs and benefits		**Type**	**Time frame**	**Extensive green roofs**			**Intensive green roofs**		
				Value (€/m^2)		Function	Value (€/m^2)		Function
				Low scenario	High scenario		Low scenario	High scenario	
Private	Initial costs	Cost	One time	90	113	Uniform	127	440	Uniform
	Longevity	Benefit	Every 20 years	23.6		Constant	23.6		Constant
	Energy cost savings								
	-cooling	Benefit	Annual	0.14	0.52	Uniform	0.14	0.52	Uniform
	-heating	Benefit	Annual	0.17		Constant	0.17		Constant
	Noise reduction	Benefit	One time	25		Uniform	25		Uniform
	Storm water management	Benefit	Annual	0	0.07	Uniform	0	0.07	Uniform
	Tax reduction	Benefit	Annual	0	48	Uniform	0	48	Uniform
	Property value	Benefit	One time	105	140	Uniform	139	498	Uniform
	Operation and maintenance	Cost	Annual	0.5	11	Uniform	0.5	11	Uniform
Social	Urban heat island effect	Benefit	Annual	0	0.01	Uniform	0	0.01	Uniform
	Air quality improvement	Benefit	Annual	0	0.02	Uniform	0	0.02	Uniform
	Flood risk reduction	Benefit	Annual	0	0.02	Uniform	0	0.02	Uniform
	Biodiversity	Benefit	One time	0	0.01	Uniform	0	0.01	Uniform
	Aesthetics	Benefit	One time	0	6.70	Uniform	0	35	Uniform

Source: Konášová (2018)

Table 3 summarize the personal and public costs and benefits of implementation of green roofs. Benefits are dependent on a number of different factors such as location of building, height of building. The Table 1 shows two scenarios: extensive roofs and intensive roofs. The analysis shows that the private benefits are mostly high enough to cover the current level of the private costs of the most common available green roofs. Considering the membrane longevity or the increase of property value, these benefits may particularly justify the additional initial costs of green roofs. It is important to mention that every case is unique with regard to location in the city, type of building, or type of use.

3.7 Disadvantages of green roofs

The main disadvantage of green roofs is the initial cost of their installation that can be double that of a standard roof (Getter et al., 2006). The additional mass of the growing media and retained water place a large strain on the structure support of buildings. This causes complications with wild implementation of intensive green roofs based on the lack of existing buildings that are able to support a large amount of added weight.

The maintenance costs could be higher because green roofs require significantly more maintenance compared to a conventional roof. Standard maintenance includes controlling plants and moisture levels, removing debris, fertilizing substrate and deadhead trimming. However, these maintenance costs can be minimized with appropriate choice of roof systems.

Another disadvantage of green roofs can be some unwanted species of wildlife, which are attracted by plants. The wildlife includes pest insects, which could easily infiltrate into buildings through open windows.

3.8 Green roof legislation

In several countries, it is possible to find many laws that in some cases require the green roof installation, for example: Toronto was the first city in North America that passed a bylaw about green roofs in 2009 which requires from all new commercial buildings, residential and industrial, with an area of 2,000 square meters, the installation of green roof. Nowadays, Toronto provides a subsidy of 50 Canadian dollars per m^2 (Bass et al., 2013).

The results of several years of research on the benefits of green roof have led to a change in construction and building laws in Switzerland. In Basel, Zurich and Lucerne, the regulation of land uses requires the installation of green roofs for areas larger than 500 square meters as part of biodiversity strategy to maintain natural and cultural heritage (Brenneisen, 2003).

In Germany, since 1998, the Construction Law requires that, in some cases, installation of green roofs. Currently, 48 German cities provide financial support for green roofs. Approximately 35 % of all cities have integrated green roofs in their laws and municipal regulations. The 86 million square meters of green roofs have already been installed, which makes 14 % of the total flat roof area in Germany. The German Green Building Association has monitored the continuing trend of the market since 2008, which shows that the market is increasing by an average of 5 % per year (EFB, 2015). As can be seen in Table 4, Germany is the country with more square meters of green roofs in Europe.

Table 4: Growth of green roofs in Europe

Target Country	Green Roof Stock total m² (2014)	Green Roofs new/year m²	Ratio extensive %	Ratio intensive%	Yearly sales figures €
Austria	4 500 000	500 000	73%	27%	27 350 000
Czech Republic	110 000	20 000			
Germany	86 000 000	8 000 000	85%	15%	254 000 000
Hungary	1 250 000	100 000	35%	65%	5 662 500
Scandinavia (S, N, DK)		600 000	85%	15%	16 050 000
Switzerland		1 800 000	95%	5%	51 300 000
UK	3 700 000	250 000	80%	20%	28 000 000
	95 560 000	**11 270 000**			**382 362 500**

Source: EFB, European Federation Green Roofs & Walls (2015), date of CR by SZUZ (2018)

The new French law, which was passed in 2015, requires that roofs of all new buildings constructed in commercial zones have to be covered by green roofs or photovoltaic panels. This law should bring changes to the nation’s skylines and improve the efficiency of all new commercial constructions.

In 2015 in Brazilian city Recife, municipal council approved the Green Roof Law No.18,112/2015, which requires green roof installation of all residential and commercial buildings with the roof more than 400 square meters. The main purpose of this law was to reduce energy consumption for air conditioning systems and improve the living conditions of city residents.

Czech Republic

The new subsidy program New Green Savings Programme[4] was extended to support the implementation of green roofs in 2017. The intention of the Ministry of Environment is to offer financially support for other "eco tools" to improve current environment. This subsidy provides up to 19.5 €/m^2 (500 CZK/m^2) with regard to green roof's contribution of energy savings for heating and cooling, especially in period of temperature fluctuations. The installation of green roofs is supported on both existing and new building.

Based on information from agency Svaz zakládaní a údržby zeleně (2018), it was calculated that 195,000 m² of green roofs were added in the Czech Republic in 2017, equivalent to 18 football pitches or 4.3 multiple of Wenceslas Square. Compared to 2016, when the green roof area grew to 130,000 m², it is a year-on-year increase of 50 %. In 2015, the measurement was not undertaken. Significant year-on-year growth is mainly due to public support for green roofs under New Green Savings Programme.

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[4] NZU (2017) *Nová zelená úsporám: nově na výstavbu nízkoenergetických bytových domů, zelené střechy a využívání tepla z odpadní vody*, Available Online: http://www.novazelenausporam.cz

4 CASE STUDIES

The investigations of the potential of precinct scale implementation of green roofs in mitigating the urban heat island effect in this research are undertaken by three case studies (600 m x 600 m grid) with different climate condition.

4.1 CZECH REPUBLIC – PRAGUE

The city of Prague (50°05'N 14°25'E) is the capital and largest city of the Czech Republic. The city is situated in the north-west of the country on the Vltava River, the city is home to 1.26 million people, while its larger urban zone is estimated to have a population of nearly 2 million.

The center of Prague is located in Valley of Vltava River and its tributaries. The erosive action sculpted rugged relief with the lowest point in Suchdol (177 m above sea level) and the highest point on Telecek peak (399 m above sea level). In term of geomorphological classification, the most of the area of the capital Prague belongs to the whole Prague plateau.

4.1.1 Climatic condition of Prague

The climate in Prague is cold and temperate. Based on Köppen climate classification system, Prague lies between oceanic climate and humid continental climate. The winters are relatively cold with average low temperatures of -4 °C, and with little sunshine. Snow cover is common between mid-November and late March although snow accumulations of more than 20 cm are occasional. There are also a few periods of mild temperature in winter. Summers usually bring plenty of sunshine and average high temperature of 24 °C. City is a region with a significant rainfall, even in the driest month.

4.1.2 Study area in Holešovice

Holešovice is Prague’s neighborhood that was attached to Prague in 1884 as historically the first village, which was not the city at the time of annexation. The main part of Holešovice is located on Prague’s Vltava river meander on its left bank. Almost the entire territory belongs to the Prague 7, but small part in the southwest (the coast of the Vltava River between the Čechův most and U plovárny street) belongs to the Prague 1.

The first recorded mention of Holešovice dates back to 1228. Originally a small farming village Holešovice in place of Prague-Holešovice station grew throughout the territory in the last third of the 19th century and turned into one of the most important industrial suburb of Prague. Until then Holešovice had been uninhabited because of floodplains of Vltava meander. In 1928, the Libeňský Bridge was open to connect this neighborhood with the rest of the districts. The conventional location of Holešovice led to a significant construction growth of office buildings and residential complexes after the year 2000.

Holešovice was chosen as a study area (Figure 26) based on previous study called UHI[5] of collaboration of Prague Institute of Planning and Development, Department of Meteorology and Environment of Mathematics and Physics at Charles University in Prague, and the Czech Hydrometeorological Institute, which tried to evaluate the effect of urban solutions and other strategies (e.g.: green roofs, parks, urban greenery and trees) to reduce the UHI. One of the main reasons of selection of Holešovice is possibility to install green roofs because many roofs are flat and unused. The investigated area is also typical example of brownfield with anticipated change of land to new constructions.

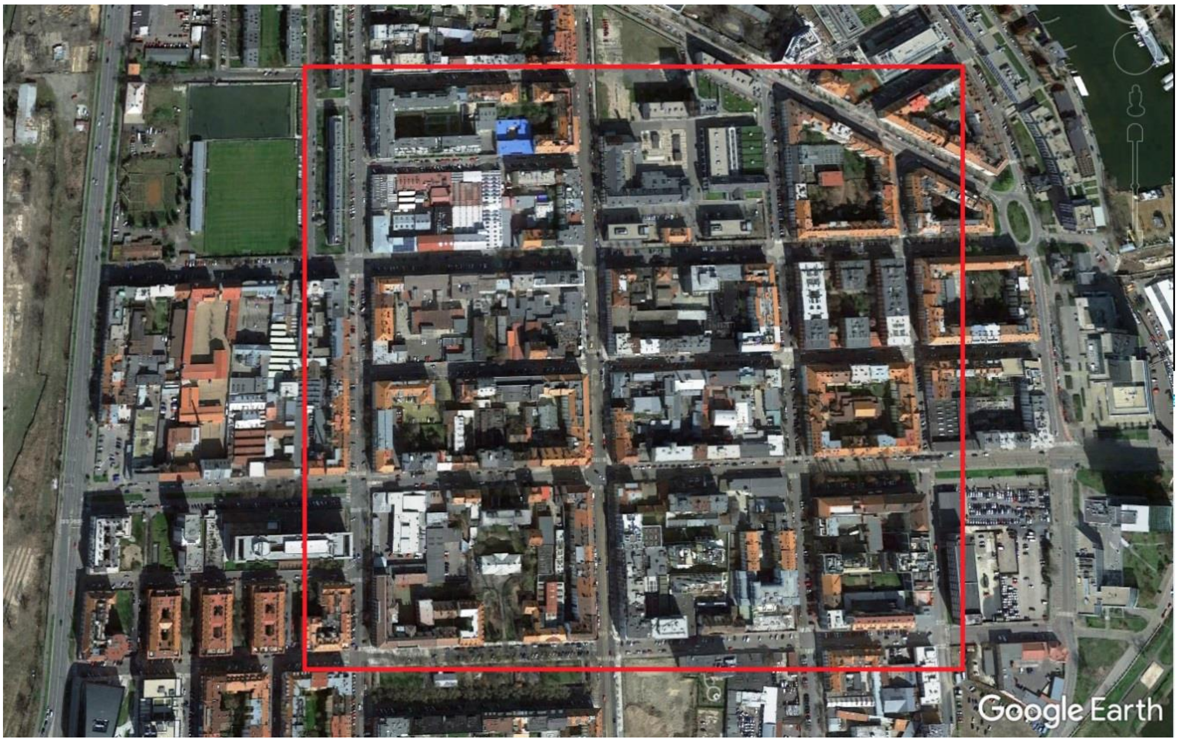

Figure 26: Study area in Holešovice

Source: Google Earth

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[5] UHI Project Online: http://eu-uhi.eu/

4.2 BRAZIL - RIO DE JANEIRO

The city of Rio de Janeiro (22°54'10"S 43°12'28"W) is a Brazilian city, located in the southeast of the country, at an altitude of about 10 meters in relation to the mean sea level. Rio de Janeiro is the capital of the state of Rio de Janeiro, the third most populous state in Brazil. The city's metropolitan area is the second most populous metropolitan area in Brazil and seventh most populous in the Americas, which has 1197 km^2 surface area. In 2014, according to Brazilian Institute of Geography and Statistics (IBGE, 2014) the population of Rio de Janeiro was 6,453,682.

The diverse landscape of the metropolitan area of Rio de Janeiro, which is surrounded by the Atlantic Ocean and Guanabara Bay in the east, contributes to the significant variability of weather elements such as temperature, precipitation, humidity, wind, cloud cover, and evaporation. Rio de Janeiro is located around the Tijuca Massif, the Gericinó-Mendanha Massif in the north and the Pedra Branca Massif in the west, all affecting such mentioned climate.

4.2.1 Climatic condition of Rio de Janeiro

According to the Köppen climate classification system, climatic condition of Rio de Janeiro is Atlantic tropical with an average air temperature of 16 °C throughout the year and a dry season in which the average monthly precipitation is less than 60 mm for at least one month of the year. The average annual temperature varies between 23 °C and 24 °C, where the highest monthly average occurs during summers in February (28.7 °C), and the lowest monthly average occurs during winters in July (21.3 °C) (INMET, 2015).

4.2.2 Study area in Copacabana

Copacabana neighborhood is located in the southern area of the city of Rio de Janeiro. It is known for its beach that carries the same name as the district and is considered one of the most famous in the world. In 1892, the inauguration of the tunnel Velho, which connected neighborhood Botafogo with Copacabana, allowed to integrate this neighborhood with rest of the city. As a result of the demand to live there by the growing middle class, the neighborhood began to expand vertically up to thirteen-story. Nowadays, residential buildings with ten to twelve-story built next to each other dominate the neighborhood. Houses of two or three-story are rare. According to IBGE (2014) total population of

Copacabana was 147,021 inhabitants in 2014. The lack of green spaces inside of the densely built-up area of neighborhood creates many heat islands. For this reason, Copacabana was selected as a study area to demonstrate the possibility to mitigate the urban heat island effect. The exact location of the study area is shown in Figure 27.

Figure 27: Study area in Copacabana
Source: Google Earth

As can be seen from Figure 27, the Copacabana neighborhood is densely build-up area of different constructed materials properties, which influence (together with the vegetation and the paved surfaces) the amount of thermal energy accumulated and radiated to the atmosphere.

The spatial characterization of the chosen area was elaborated within the ENVI software by remotely sensed satellite images to determine the roof systems utilized in Copacabana district. Three different systems of conventional roofs were defined through satellite images; flat concrete roof, pitched roofs with ceramic tile, and tin roof. This analysis of the roofs took into consideration the color and shape of the roofs. It was estimated that 85 % of roofs are flat concrete roofs, 13 % of pitched roofs with ceramic tiles, and 2 % of tin roofs.

The green roofs were not found through the satellite images or Google Earth in any of the randomly selected areas. In some cases, vegetation in the form of palm trees or flowers was possible to find on rooftops.

4.3 AUSTRALIA – SYDNEY

Sydney is the largest and most populous city in Australia, the capital of New South Wales. Sydney is located on the northeast coast of the Tasman Sea. With its population of more than 4.5 million, it is the most populous city in Oceania. Sydney is 43rd in terms of the size of its urban footprint of 2,037 square kilometers. It is also the country’s most dense, with 1,900 people per square kilometer (ABS, 2009). The city is built on the hills around the fragmented and deep-cut port of Port Jackson, which is now called Sydney Harbor, place where Sydney Opera House and Harbor Bridge are located. Near the metropolitan area, there are national parks and coastal areas that contain lots of bays, rivers, and beaches.

4.3.1 Climatic condition of Sydney

The climate of Sydney is humid subtropical based on the Köppen climate classification system, shifting from cool and mild in winter to hot and warm in the summer, with no extreme seasonal differences in regard to proximity to the ocean. Precipitation differs across the region, with areas adjacent to the coast being the wettest. The city has 103.9 clear days annually, with the monthly percent possible sunshine ranging from 53 % in January to 72 % in August. Sydney's heat is mostly dry in spring, but usually humid in the summer. The humidity is usually low as such high temperatures are brought by searing winds from the Australian desert (Australian Government, 2018).

4.3.2 Study area in Parramatta

Parramatta is a prominent suburb of Sydney, in the state of New South Wales, Australia, 23 kilometers west of its central business district on the banks of the Parramatta River with population of 234,000. Parramatta is the administrative seat of the City of Parramatta and is often regarded as the second central business district (CBD) of Sydney.

Parramatta, founded by the British in 1788, the same year as Sydney, is the oldest inland European settlement in Australia and the economic capital of Greater Western Sydney. Since 2000, many government agencies have relocated to Parramatta from the center of Sydney in order to create the second central business district. The center of Parramatta is mostly composed of two-storey residential buildings, two-storey parking garages, and high-rise office buildings.

The Parramatta CBD is considerably warmer than Sydney CBD in the summer due to the urban heat island effect and its inland location. In extreme cases, the suburb can be 5 - 10 °C warmer than the city, especially when sea breezes do not penetrate inland on hot summer and spring days. For example, on 28 November 2009, the Sydney reached 29.3 °C, while Parramatta reached 39.0 °C, almost 10 °C higher (Australian Government, 2018). Northwest fronts can occasionally bring hot winds from the desert that can raise temperatures higher than 40 °C usually from November to February.

The Australian Greens[6] observed the temperature records and found that a strong existence of the urban heat island effect in Parramatta, Western Sydney. Western Sydney is particularly exposed, as, unlike the coastal suburbs, it does not receive the moderating influence of a cooling sea breeze. Based on these observations, the Parramatta was selected as third case study. Figure 28 shows the selected area of Parramatta suburb. The high concentration of buildings with the large amounts of paved and dark colored surfaces like roads, roofs, and car parks and the small amounts of green areas can be observed from the Figure 28.

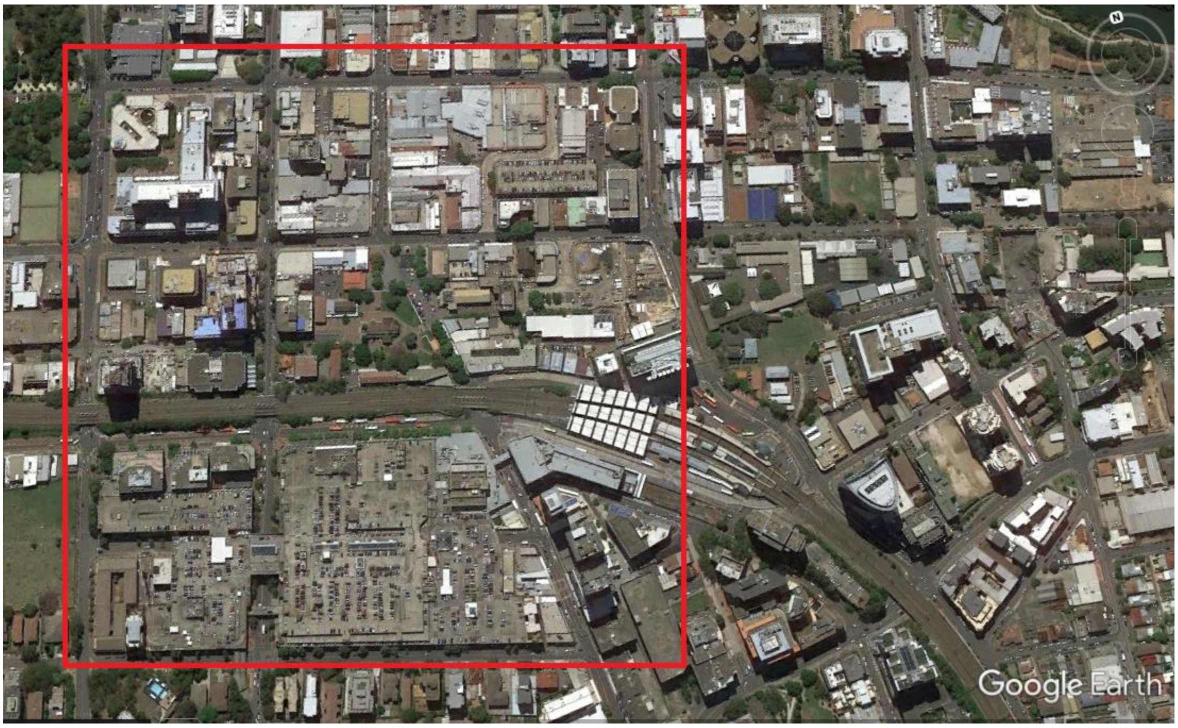

Figure 28: Study area in Parramatta

Source: Google Earth

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[6] The Australian Greens is a green political party in Australia, https://greens.org.au/

5 COMPARATIVE ANALYSIS

The potential of green roofs to ameliorate the urban heat island effect is determined based upon simulations conducted by ENVI-met simulation software. The investigations of this thesis are accomplished in two parts. First part is focused on simulation of the potential of precinct scale green roofs in specific simplified urban conditions, one square section of Holešovice district in Prague (temperate climate), one square section of Copacabana district in Rio de Janeiro (tropical climate), and one square section of Parramatta district (subtropical climate) in Sydney to measure their effectiveness in real conditions. In part two, the results from computer simulation are taken into consideration to calculate the reduction in energy demand for space cooling.

5.1 COMPUTER SIMULATION

ENVI-met (version 4.0, freeware for MS Windows[7]) is selected due to the capabilities of this software in modeling greenery and urban fabrics. ENVI-met is a three-dimensional microclimate numerical model that can simulate the surface-plant-air interactions, solar path, buildings and vegetation within urban environment and is based on the fundamental laws of fluid dynamics and thermodynamics. It shows a good resolution that satisfactorily models small-scale interactions between buildings, surfaces, and plants. In a comparative review of existing tools to assess physical parameters of urban microclimate, Moonen et al. (2012) acknowledge ENVI-met as a suitable tool for complex models, which takes into account a broad spectrum of relevant and determinant factors. The technical aspects and modules used in ENVI-met are given in Table 5 (Bruse et al., 2010).

Table 5: Aspects and models of ENVI-met software

Atmosphere	Soil system	Vegetation	Surfaces	Biometeorology[8]	Behind the scenes
Wind	Temperature	Foliage temperature	Ground surface fluxes	PMV-Value The climBOTs	The Mathematics
Temperature	Water flux	Heat exchange	Fluxes at walls/roofs		
Vapor	Water bodies	Vapor exchange	Heat transfer		
Turbulence		Water interception			
Pollution		Water transport			

Source: ENVI-met manual

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[7] Freeware at http://www.envi-met.com

[8] Biometeorology is an interdisciplinary science studying the interactions between atmospheric processes and living organisms - plants, animals and humans.

The first step in order to use ENVI-met is to create the area input file. This file combines the height and location of buildings, location of plants, distribution of surface materials and soil types, location of gas sources, position of receptors (i.e. selected points inside the designed area, where processes in the atmosphere and the soil are monitored in detail), database links and geographic position of the location on the Earth. These characteristics are set by using grids. The next step is the establishment of the configuration file which defines the settings for the simulation to run. These settings are the area input file, the name of the output file, the day the simulation runs, the meteorological settings and the plant database. The inserted data is specified in Table 6.

Table 6: Meteorological inputs

Scenarios	**Czech Republic - Prague Holešovice**	**Brazil - Rio de Janeiro Copacabana**	**Australia - Sydney Parramatta**
Start simulation at day	20.06.2016[9]	21.12.2016[10]	21.12.2016[11]
Start simulation at time	9:00	9:00	9:00
Total simulation time in hours	24	24	24
Save model state each min	60	60	60
Wind speech in 10 m above ground (m/s)	4	6	4
Wind direction (0:N, 90:E, 180:S, 270:W)	292	90	130
Roughness	0.1	0.1	0.1
Initial temperature atmosphere (°C)	16	28	26
Specific humidity in 2500m (g water/kg air)	9	21	13
Relative humidity in 2m (%)	79	90	61

Source: Author

The model requires a user-specified area input file that defines the 3D geometry of the model environment such buildings heights, type of vegetation, soil and surface types (Table 7). The examined areas of case studies are 600 m x 600 m based on limitation of free version of ENVI-met. Average building height for Holešovice district is estimated 15 m, for Copacabana district 36 m and for Parramatta 12, 26 and 38 m based on dissimilar heights of buildings.

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[9] Midsummer in northern hemisphere

[10] Midsummer in southern hemisphere

[11] Midsummer in southern hemisphere

Table 7: Selected input parameters of buildings and vegetation

Category	**Czech Republic - Prague Holešovice**	**Brazil - Rio de Janeiro Copacabana**	**Australia - Sydney Parramatta**
Building inputs			
Buildings average height	15	36	12 - 26 - 38
Material of conventional roof	concrete slab	concrete slab	concrete slab
Type of vegetation used on GR			
Extensive GR	grass 50 mm	grass 50 mm	grass 50 mm
Intensive GR	bushes 500 mm	bushes 500 mm	bushes 500 mm

Source: Author

In the end, the simulation runs and gives temperature results for every period of the time selected by the configuration file. Leonardo is used to visualize and analyze the received results. This software is the interactive visualization and analysis tool for ENVI-met and BOT world. It can turn simulation results from charts into simple line charts to complex 3D animations. It includes a special interface to ENVI-met data files which allows a simple navigation through the data. After selecting the variables needed for the simulation, the map can be extracted either in 2D cut or 3D cut.

The urban blocks, which were selected and modeled in ENVI-met, of the current state (buildings with conventional roofs) and the state in case of installation of green roofs on same existing buildings are examined (Figures 29, 30, 31, 32, 33, and 34). The conventional roof scenario is the one in which these is absence of green areas on roofs in order to observe how green roofs affect the temperature, and therefore mitigate the UHI effect.

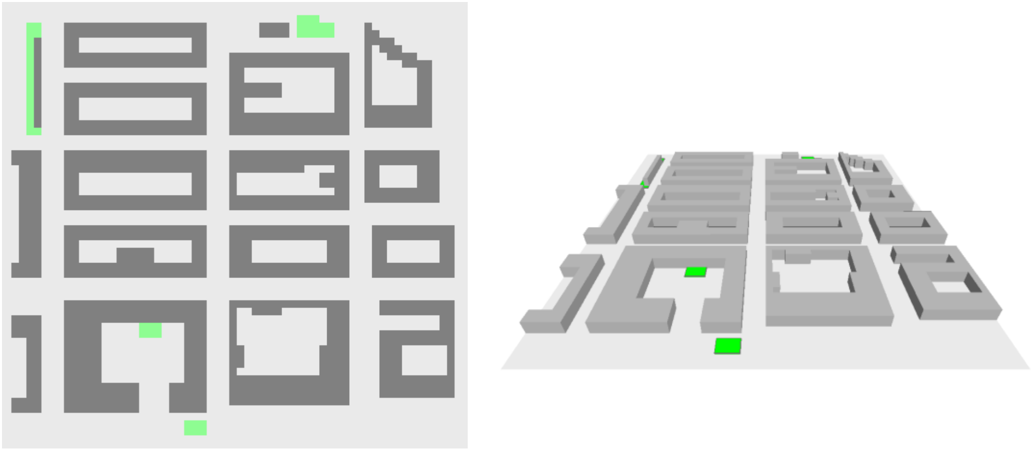

Figure 29: The conventional roof scenario of Holešovice in 2D and 3D, input file

Source: Author

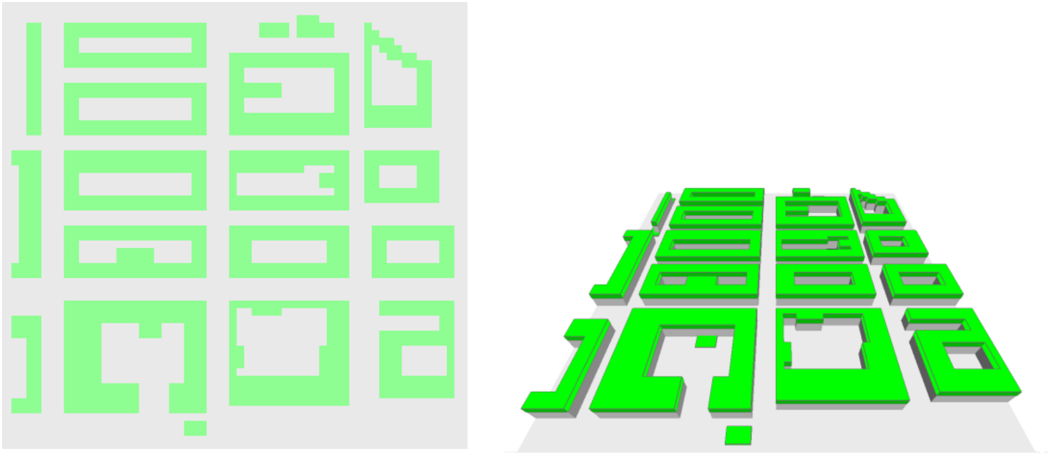

Figure 30: The green roof scenario of Holešovice in 2D and 3D, input file
Source: Author

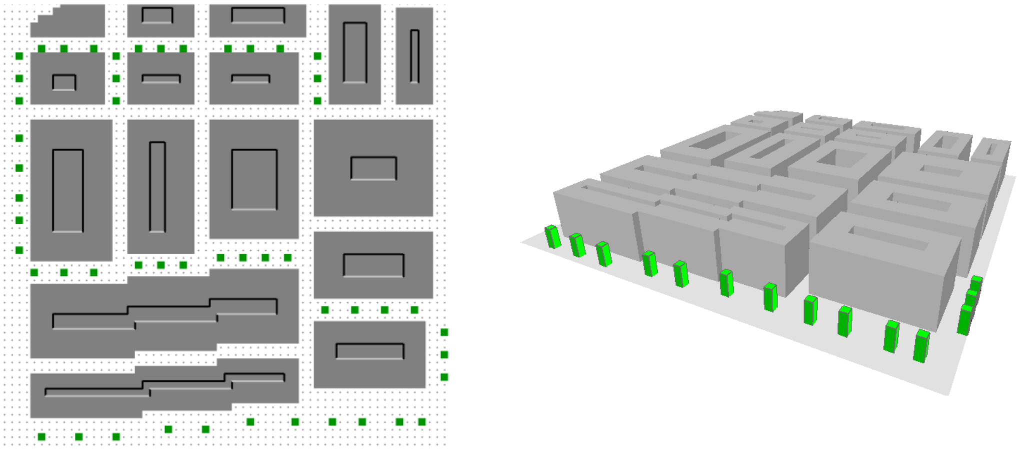

Figure 31: The conventional roof scenario of Copacabana in 2D and 3D, input file
Source: Author

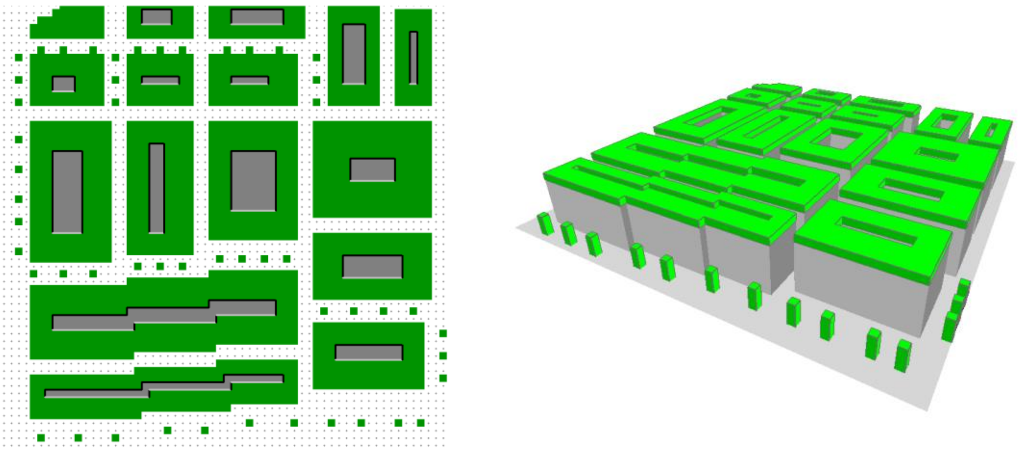

Figure 32: The green roof scenario of Copacabana in 2D and 3D, input file
Source: Author

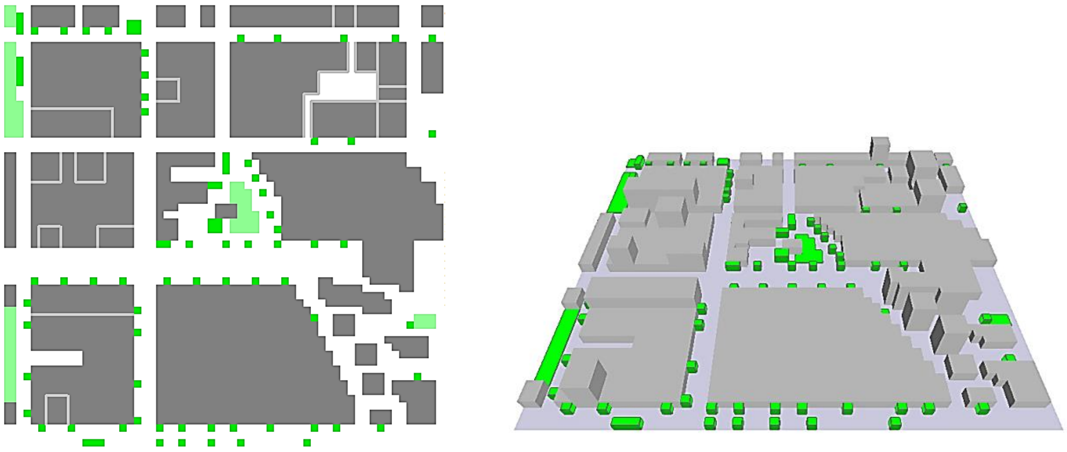

Figure 33: The conventional roof scenario of Parramatta in 2D and 3D, input file

Source: Author

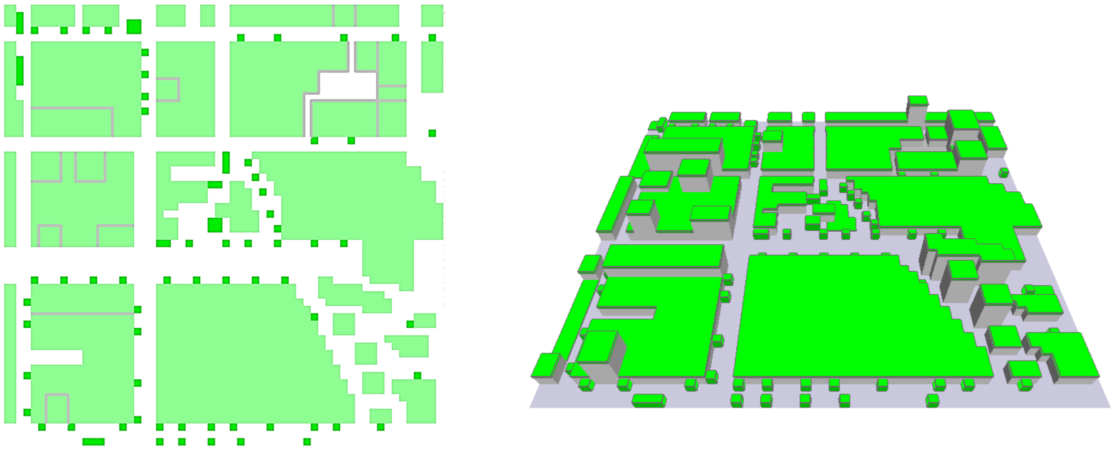

Figure 34: The green roof scenario of Parramatta in 2D and 3D, input file

Source: Author

5.2 ENERGY SAVINGS ANALYSIS

A detailed analysis of cooling energy use in the future is needed to better understand the impact of urban heat island effect on building energy consumption. In many studies, the degree-day method is generally used with future weather data to determine the impact of climate change on building energy consumption (Rosenthal, 1995). The degree-day analysis uses the balance point temperature of a building, that in which the building does not require either heating or cooling. The choice of balance point temperature can be different for each region and each type of building. The Cooling Degree Days (CDD) is calculated hourly over a year as

$$CDD = \frac{\sum_{i=1}^{24}(T_o - T_b)}{24} \qquad if\,(T_o - T_b) > 0 \tag{3}$$

where T_b is the balance point temperature; the number of degrees that a day's average temperature is above this point and people start to use air conditioning to cool their buildings. T_o is the outdoor daily temperature. This method can offer a quick estimate of the impact of climate change on buildings. The studies have often found that this method would lead to large deviations as compared to energy simulations Scott et al. (1999). Thus, hour-by-hour energy simulation is better for studying the impact of urban heat island effect on energy consumption in buildings.

The degree-days figure for a given month or week is the accumulated total of daily results over the period in question. The daily result for cooling degree-days D_C, is selected from the following Table 8. The calculation requires daily measurements of maximum and minimum outside air temperatures (T_{max} and T_{min}) and a base temperature (T_{base}).

Table 8: Formulae for calculation cooling degree-days

Condition	Formula used
$T_{min} < T_{base}$	$D_c = 0$
$(T_{max} + T_{min})/2 < T_{base}$	$D_c = (T_{max} - T_{base})/4$
$T_{max} < = T_{base}$	$D_c = (T_{max} - T_{base})/2 - (T_{base} - T_{min})/4$
$T_{max} > T_{base}$	$D_c = (T_{max} + T_{min})/2 - T_{base}$

Sources: Vesma (2017)

The energy analysis evaluates impact of the UHI effect on energy demand for space cooling in three different cities with different climate conditions. The selected areas represent the mixture of residential buildings and commercial buildings.

5.2.1 Calculation of energy use for cooling

Cooling degree day figures come with a base temperature, and provide a measure of how much (in degrees), and for how long (in days), the outside temperature was above that base temperature. CDD is an indicator of the summer temperature and, thus of cooling requirement. It is calculated as the sum over each day of the cooling period of the difference between the average daily temperature and a reference indoor temperature. The most readily available cooling degree days come with the baseline temperature of 22 °C (recommended in the EU) (EEA, 2006). There is no harmonized method to calculate CDD.

The same building, whose characteristics were calculated in study of Elcner (2008) with a total area 100 m^2, Table 9, is used for the Czech Republic, Brazil and Australian case, for the sake of simplicity. All values from this study were in accordance with European Standards No: CSN EN 12831.

Table 9: Building’s values

	Standard		**CSN EN 12831**
Q_{hl}	total heat losses	W	8587
ε	correction factor	-	1.2 – 1.5

Sources: Thesis of Elcner (2008)

The calculating heat loss for one degree, specific heat loss for one degree will equal:

$$Q_{SH} = \frac{Q_{hl}}{\Delta T} = \frac{8587}{30.5} = 281.5 W/°C$$

To calculate energy requirement for cooling is used Eq. 4:

$$Q_{cool} = 24 \cdot Q_{SH} \cdot \varepsilon \cdot CDD \tag{4}$$

By using formula 4, the calculation of the energy needed for this building in different places according their latitude and altitude and CDD for each city, is accomplished by using software BizEE[12]. The software is based on temperature data from Weather Underground, a weather-data service with data from thousands upon thousands of weather stations worldwide. The weather stations were selected based on the location of case studies. The nearest weather station Libuš, Prague is chosen for Holešovice district, Forte de Copacabana weather station is selected for Copacabana district and Parramatta North weather station for Parramatta district.

Cooling is delivered currently almost exclusively through electric energy, therefore is necessary to take into consideration the coefficient of performance (COP) and energy efficient ratio (EER). An air conditioning system uses power to transfer heat from one space to another space. When cooling, the air conditioning system is moving heat from the place being cooled (e.g. room) to somewhere it is unwanted (e.g. outside). The COP is based on the amount of power input to a system compared to the amount of power output by that system, in Watts.

$$COP = \frac{Power\ output}{Power\ input} \tag{5}$$

The higher the COP, the more efficient the system is. This means that an air conditioning system is more efficient when the room temperature is closer to the outside temperature and will use more power when there is a larger difference in these temperatures.

An air conditioner's efficiency is measured by the energy efficiency ratio (EER) (in British thermal units [Btu] per hour) to electrical input energy (in Watt-hour).

$$EER = \frac{output\ cooling\ energy\ in\ BTU}{input\ electrical\ energy\ in\ Wh} \tag{6}$$

The higher the EER rating, the more efficient the air conditioner unit is. To convert EER to COP, it is needed to accommodate for the units used. The BTU energy and the electrical input energy could be converted to a common energy unit. One BTU equals 1055 Joules. One Wh equals 3600 Ws or 3600 J[13]. EER = 3.41xCOP

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[12] Online available: http://www.degreedays.net/

[13] *COPs, EERs, and SEERs: How Efficient is Your Air Conditioning System?*Available: http://www.powerknot. com/how-efficient-is-your- air-conditioning-system.html

5.2.2 Discounted payback period

The payback period is an important and often used indicator of an investment evaluation that gives an idea of how long the initial or additional investment capital will be at risk. The payback period is the length of time, usually in years, it will take for estimated economic benefits to recover the investment. This method is by far the most common return on investment (ROI) method used to express the return (Gallo, 2016). It is especially used for quick orientated evaluation of a certain investment, or for a quick control whether a certain investment opportunity is real in conditions of a particular business. Discounted payback period method takes into account the time value of money and is therefore an upgraded version of the simple payback period.

To calculate the discounted payback period, this formula is used (Energy Audit and Energy Assessment Decree No. 480/2012 Sb. in Karásek, 2012):

$$IN = CF_d \qquad CF_d = \frac{CF_1}{(1+r)^1} + \frac{CF_2}{(1+r)^2} + \cdots + \frac{CF_t}{(1+r)^t} \tag{7}$$

where

IN = initial investment

CF_d = periodic cash flow

r = discounted rate

t = discounted payback period

The discounted payback period is a performance measure, used to demonstrate the length of time to recoup an investment based on the investment's discounted cash flows; in this case an investment in vegetated roof.

In order to calculate the discounted payback period, firstly, the periodic cash flows of the financial benefit of green roof must be estimated. The cash flows are then reduced by their discounted factor to reflect the discounting process. Next, assuming this investment starts with a large cash outflow, the future discounted cash inflows are netted against the initial investment outflow. The discounted payback period process is applied to each additional period's cash inflow find the point at which the inflows equal the outflows. At this point, the additional cost of green roof has been paid back.

6 RESULTS

6.1 COMPUTER SIMULATION

After running the simulation for selected case study areas in three scenarios: conventional roof (CRS), extensive green roof (EGRS), and intensive green roof (IGRS), Leonardo tool is used to visualize the results. The simulation was programmed to make measurements every hour but in finale figures, the results will be presented every 8 hours, at 8h (morning), 16h (afternoon), and 24h (night). The measurements of the air temperature were taken at a standard height of 1.5 meters above the ground (Ahrens, 2007).

The following Figures 35, 36 and 37 show the comparison among three scenarios in Holešovice district, Prague, Czech Republic in degree Celsius on 20th of June, 2016. Based on the following figures, implementing greenery on the existing roofs in this area has a significant effect on reducing air temperature during the observed period.

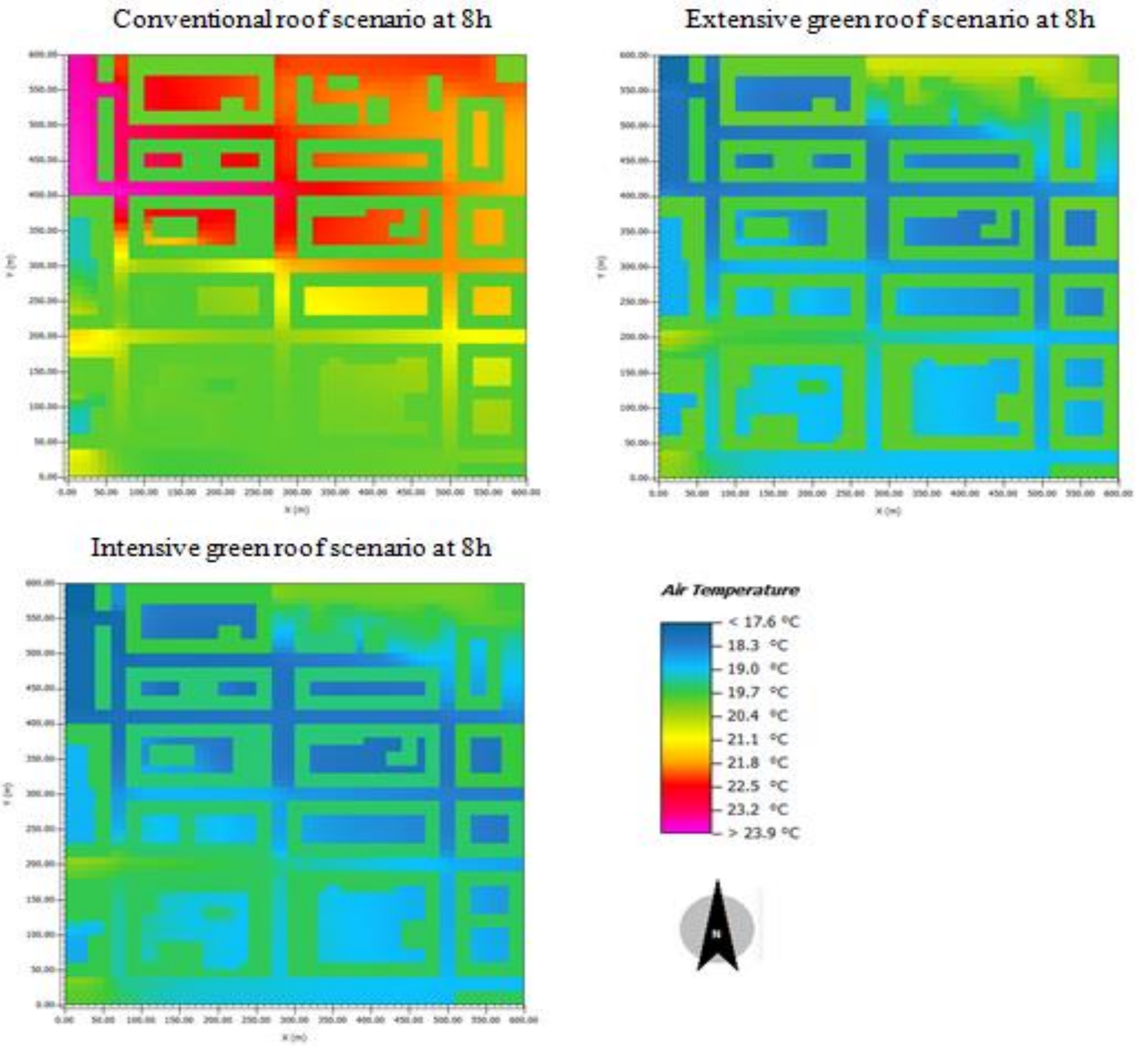


Figure 35: Air temperature at 8h, 20.6.2016 in Holešovice, Prague

Source: Author

Data of the Figure 35 shows that at 8 am the air temperature ranges from 17.6 °C to 23.9 °C with difference of 5.3 °C in built-up area of 600 m x 600 m. The highest temperature occurs in northeastern corner based on sun’s position in the morning. The simulation provides also information about minimum temperature of the conventional roof scenario (CRS) which is 18.7 °C and maximum temperature recorded is 23.9 °C. The minimum temperature of the extensive green roof scenario (EGRS) is 17.9 °C and maximum is 22.7 °C. For the last scenario of the intensive green roof (IGRS), the air temperature varies from 17.6 °C to 22.3 °C. These results show that the difference in minimum air temperature is 1.1 °C and in maximum air temperature is 1.6 °C between conventional roof and intensive green roof scenarios, in favor of intensive green roof one. From the images, it can be also seen how outdoor air temperature starts affecting temperature inside buildings.

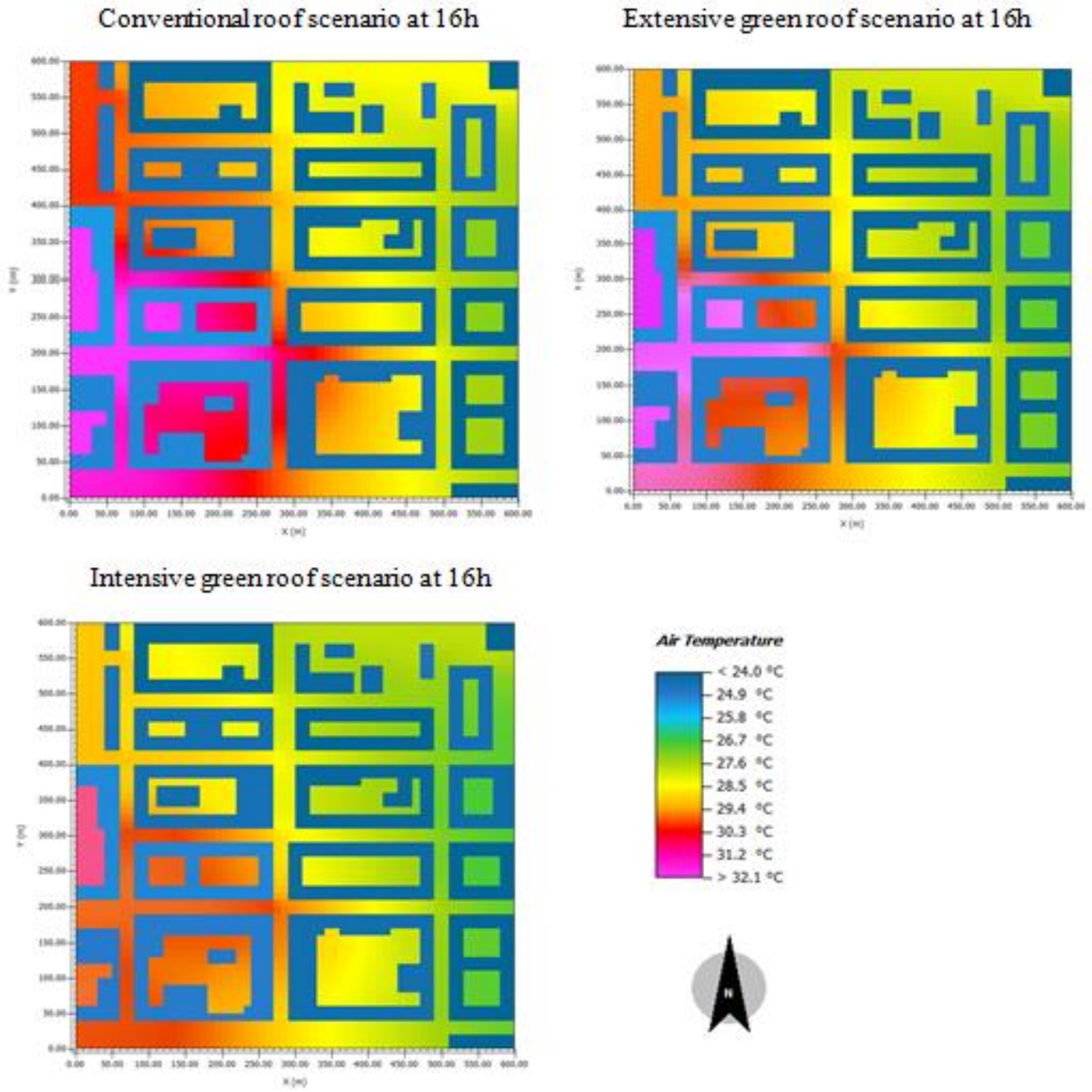
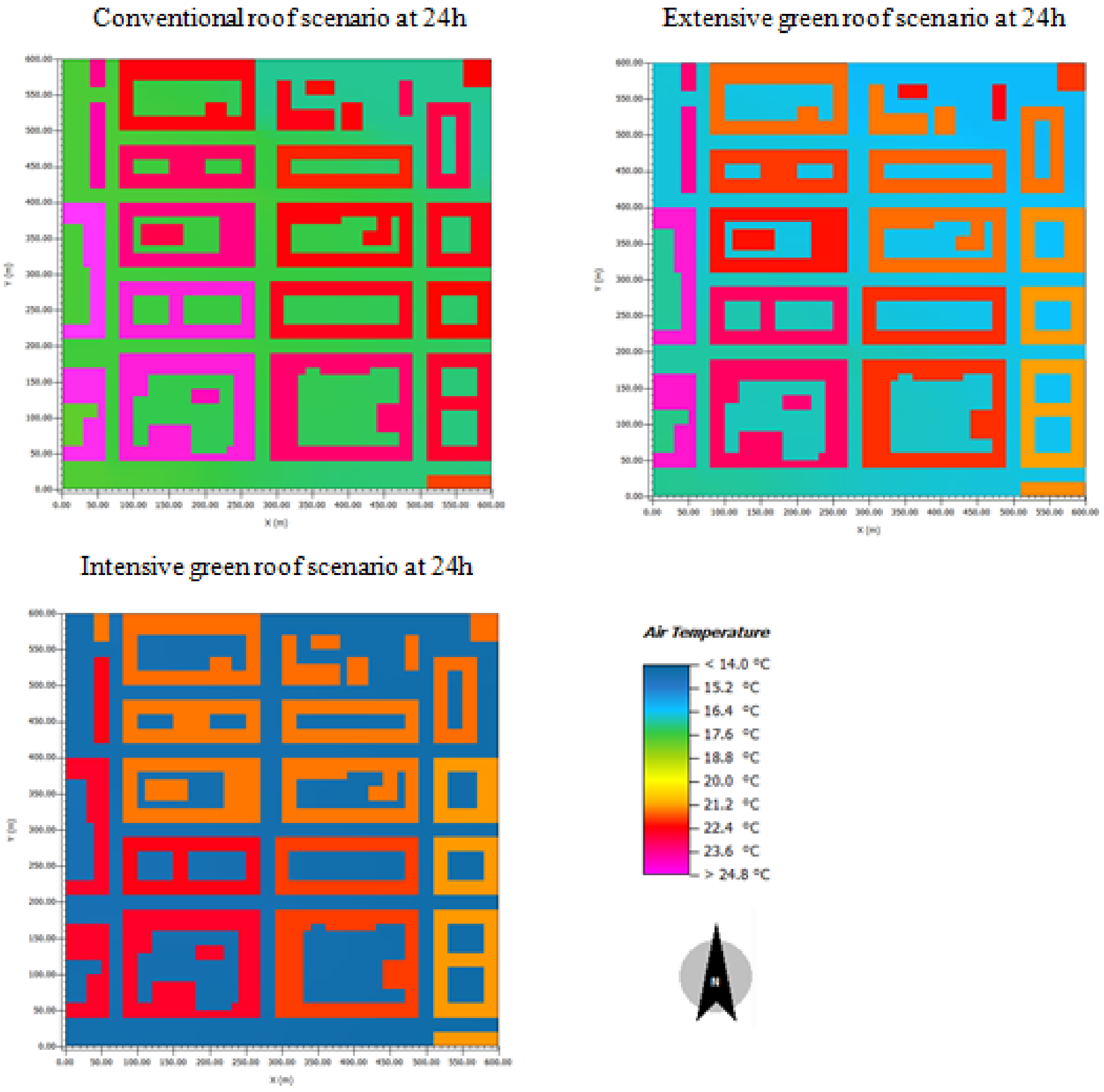


Figure 36: Air temperature at 16h, 20.6.2016 in Holešovice, Prague

Source: Author

As can be observed in the Figure 36, the air temperature varies from 24.0 °C to 32.1 °C with difference of 8.1 °C at 16h. The minimum air temperature of the conventional roof scenario is 25.4 °C and maximum is 32.1 °C. The minimum air temperature of the EGRS is 24.5 °C and maximum is 29.0 °C. In case of the intensive green roof scenario, the air temperature ranges from 24.0 °C to 28.2 °C on 20th of June. These values demonstrate that the biggest difference between the conventional roof scenario and the intensive green roof scenario in minimum air temperature is 1.4 °C and in maximum air temperature is 3.9 °C in favor of the intensive green roof scenario.


Conventional roof scenario at 24h

Extensive green roof scenario at 24h

Intensive green roof scenario at 24h

Figure 37: Air temperature at 24h, 20.6.2016 in Holešovice, Prague

Source: Author

As shown in the Figure 37, the air temperature ranges from 14.0 °C to 24.8 °C with difference of 10.8 °C at 24h. The minimum temperature of the conventional roof scenario is 15.7 °C and maximum 24.8 °C. The minimum air temperature of the EGRS is 14.5 °C and maximum is 23.0 °C. For the IGRS, the minimum air temperature is 14.0 °C and maximum is 22.2 °C. The difference in minimum air temperature is 1.7 °C between CRS and IGRS in favor of IGRS. The difference in maximum air temperature is 2.6 °C between the conventional roof scenario and the intensive green roof scenario. Moreover, it can be seen in the conventional roof scenario that buildings absorb more heat throughout the day (Figure 36) and store it during nighttime (Figure 37). This stored heat disturbs the thermal comfort of inhabitants and make them to spend more electricity for air conditioning. As a consequence, the buildings emit more heat from air conditioning process directly and power plants emission indirectly (Santamouris, 2013).

Figure 38 is a combination of a bar graph and a line graph showing the comparison among three scenarios by the temperature receptor P at a height of 1.5 m above ground level in Holešovice district, Prague, Czech Republic. The air temperature is shown on a line graph, with the figures being shown on the left side of the graph. Differences among scenarios are shown by a bar graph, with the figures being shown down the right side of the graph. The X axis shows hours of one day, 20th of June, 2016. The graph demonstrates that the peak air temperature throughout the simulated time with 1.25 °C differences between the conventional roof scenario (red line) and the intensive green roof scenario (brown line) occurred at 12:00. The air temperatures start rising rapidly at 7:00 until 13:00 when begin falling down. Furthermore, it was generated from Leonardo that the average daily air temperature of the CRS (red line) is 22.24 °C, the EGRS (green line) is 21.86 °C, and the IGRS (brown line) is 21.75 °C. As a result, the highest difference between the roof scenarios is 0.49 °C. This value is important for Chapter 5.2 to demonstrate amount of electricity consumed for space cooling which could be saved by implementation of greenery on existing roofs based on above mentioned reductions of the air temperatures.

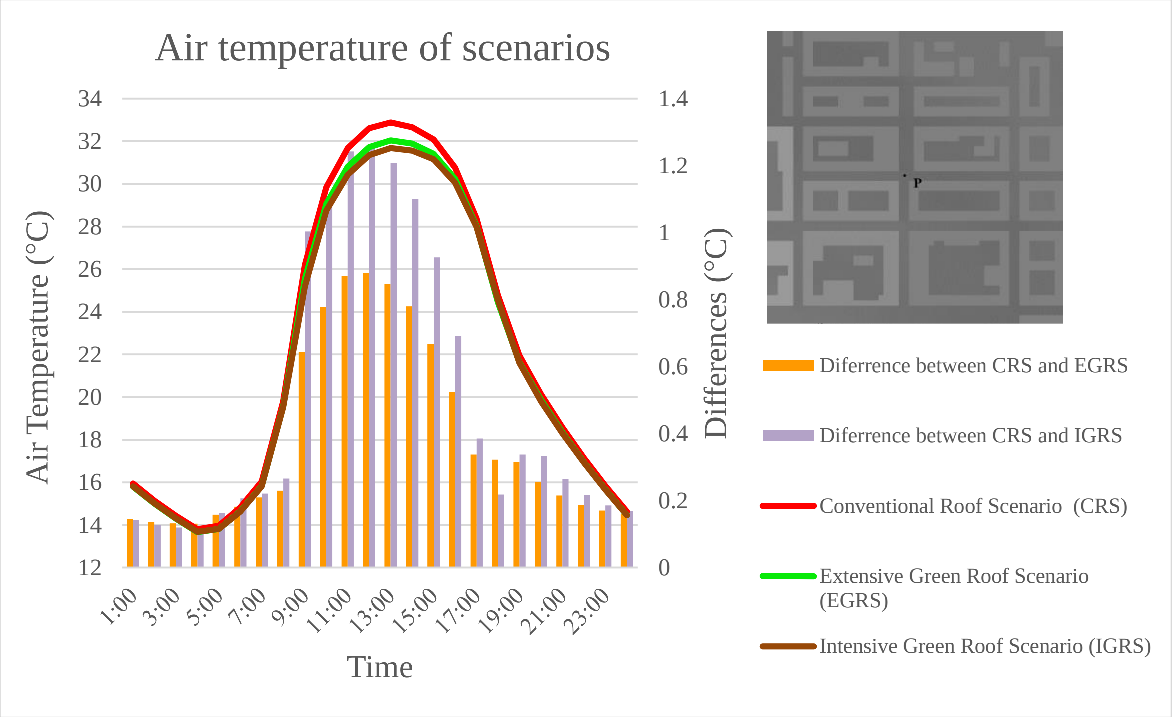


Figure 38: The receptor (P) results of scenarios, Holešovice

Source: Author

The air temperatures from Figure 38 could seem to be high in comparison to real observations. It can be caused due to two main factors. ENVI-met model is run for cloud free sky conditions thus temporal differences cannot be observed under existing cloud cover during selected period. Furthermore, the receptor, which is placed at a height of 1.5 m above the asphalt surface, is directly illuminated by the sun that leads to higher temperatures.

The following figures 39, 40, and 41 demonstrate the comparison among three scenarios in Copacabana district, Rio da Janeiro, Brazil, in degree Celsius on 21st of December, 2016. The simulated measurements of air temperature were taken at a height of 1.5 m above the ground.

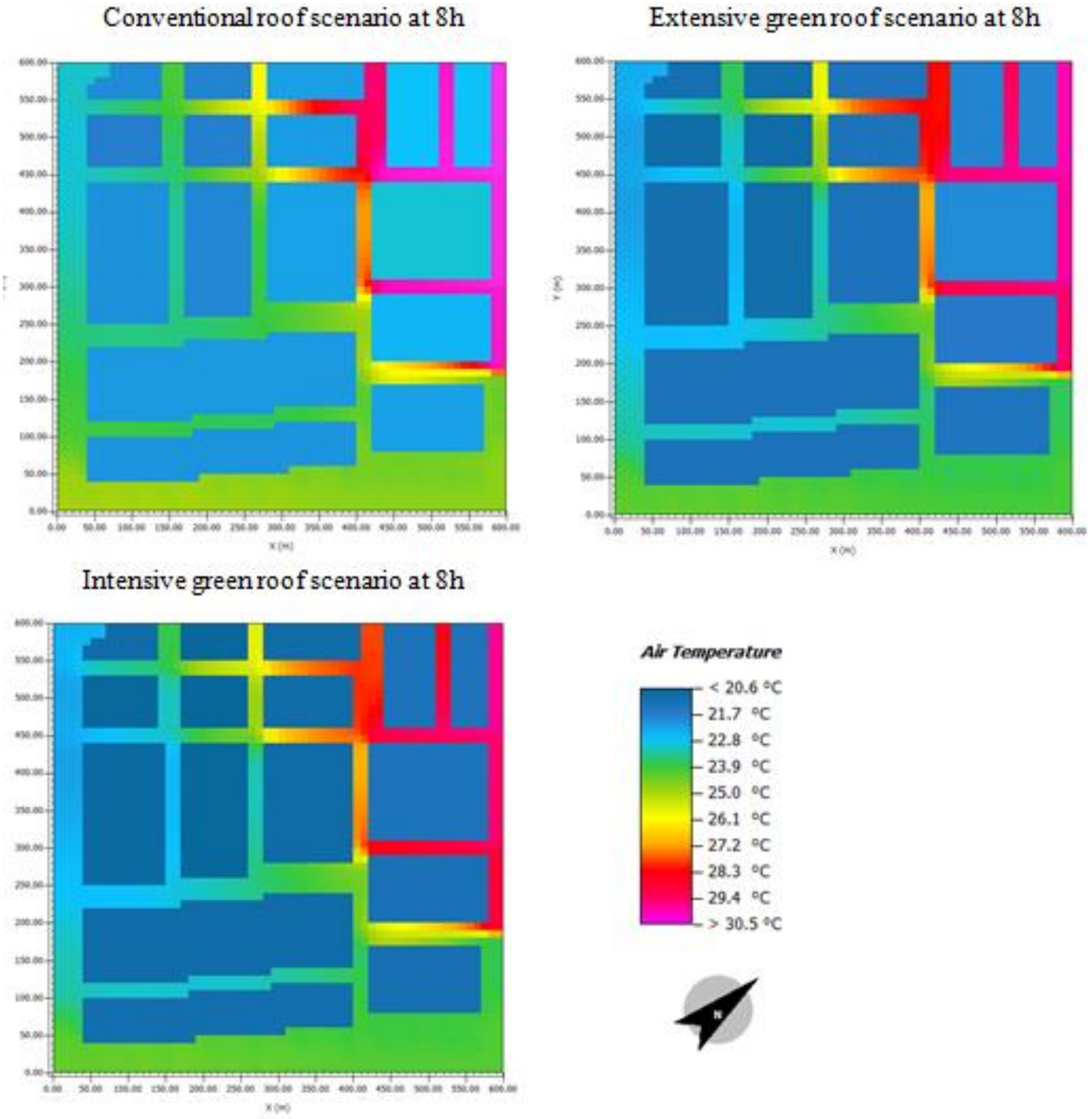
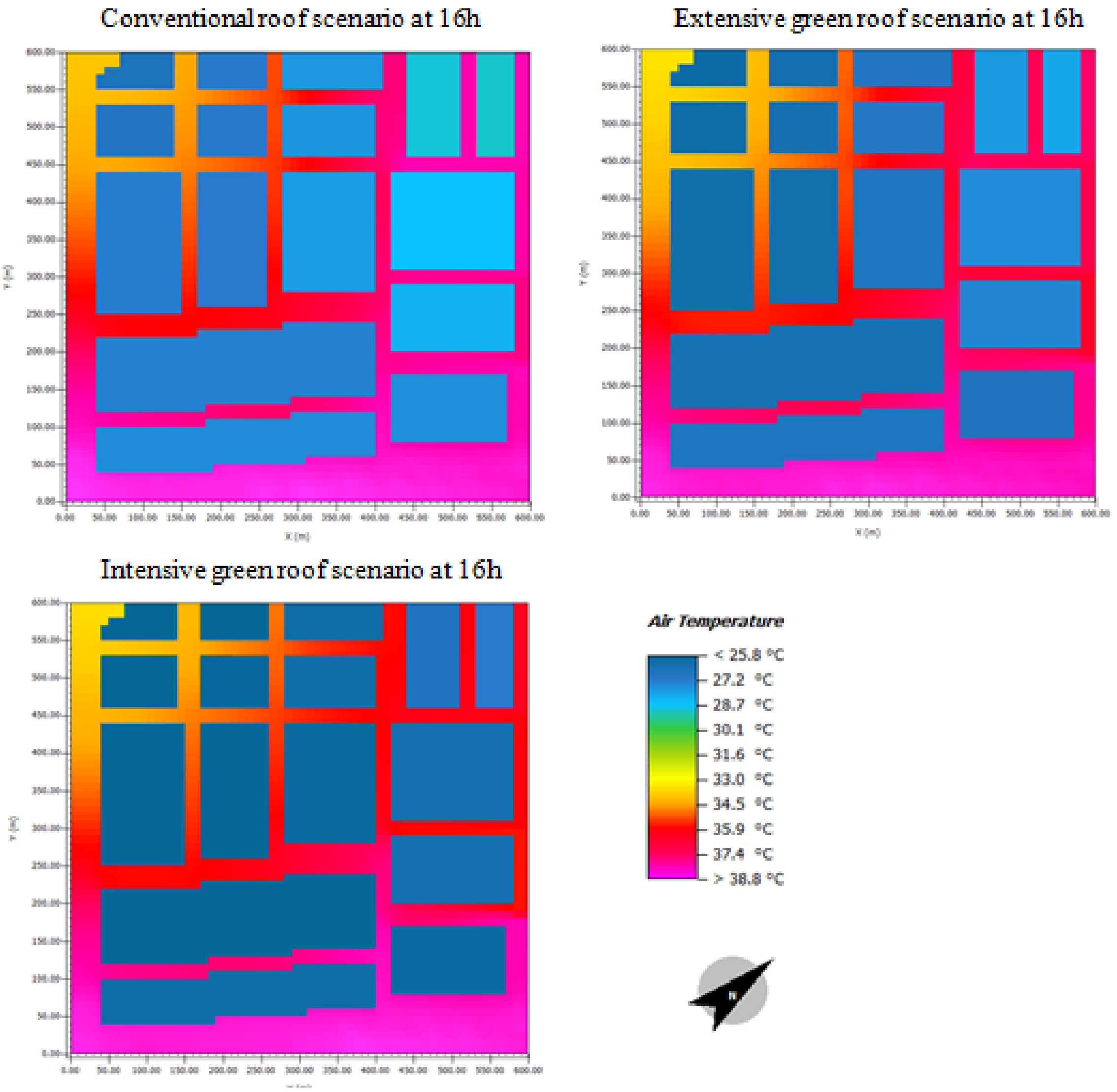


Figure 39: Air temperature at 8h, 21.12.2016 in Copacabana, Rio de Janeiro, Brazil

Source: Author

The Figure 39 shows the air temperature at 8h, which ranges from 20.6 °C to 30.5 °C with difference of 9.9 °C in built-up area of 600 m x 600 m grid. The highest temperature occurs in northeastern corner. This is caused by the sunrise in the morning. The simulation generates that minimum air temperature of the conventional roof scenario is 22.3 °C and maximum is 30.5°C. The minimum air temperature for the EGRS is 21.2 °C and maximum is 29.1 °C. In the case of the intensive green roof scenario, minimum air temperature is 20.6 °C and maximum is 28.7 °C. This points out the difference in minimum air temperature is 1.7 °C and in maximum air temperature is 1.8 ° C between the CRS and the IGRS, in favor of the intensive green roof one. In conventional roof scenario, the air temperature above the pavements and roads is higher so that affects the surroundings of buildings.


Conventional roof scenario at 16h

Extensive green roof scenario at 16h

Intensive green roof scenario at 16h

Figure 40: Air temperature at 16h, 21.12.2016 in Copacabana, Rio de Janeiro, Brazil
Source: Author

As can be seen in the Figure 40, the air temperature varies from 25.8 °C to 38.8 °C with difference of 13.0 °C at 16h. The minimum air temperature of the conventional roof scenario is 26.9 °C and maximum is 38.8 °C. The minimum air temperature for the extensive green roof is 26.1 °C and maximum is 36.9 °C. For the IGRS, the minimum air temperature is 25.8 °C and maximum 36.2 °C. These values demonstrate that the difference in minimum air temperature is 1.1 °C in maximum air temperature is 2.6 °C between the conventional roof scenario and the intensive green roof scenario in favor of green roofs. Furthermore, it can be observed that the outside air temperature affects the inside air temperature of buildings especially in case of conventional roof scenario.

Figure 41 demonstrate the air temperature during night at 24h in Copacabana neighborhood, when the urban heat island effect is more perceptible.

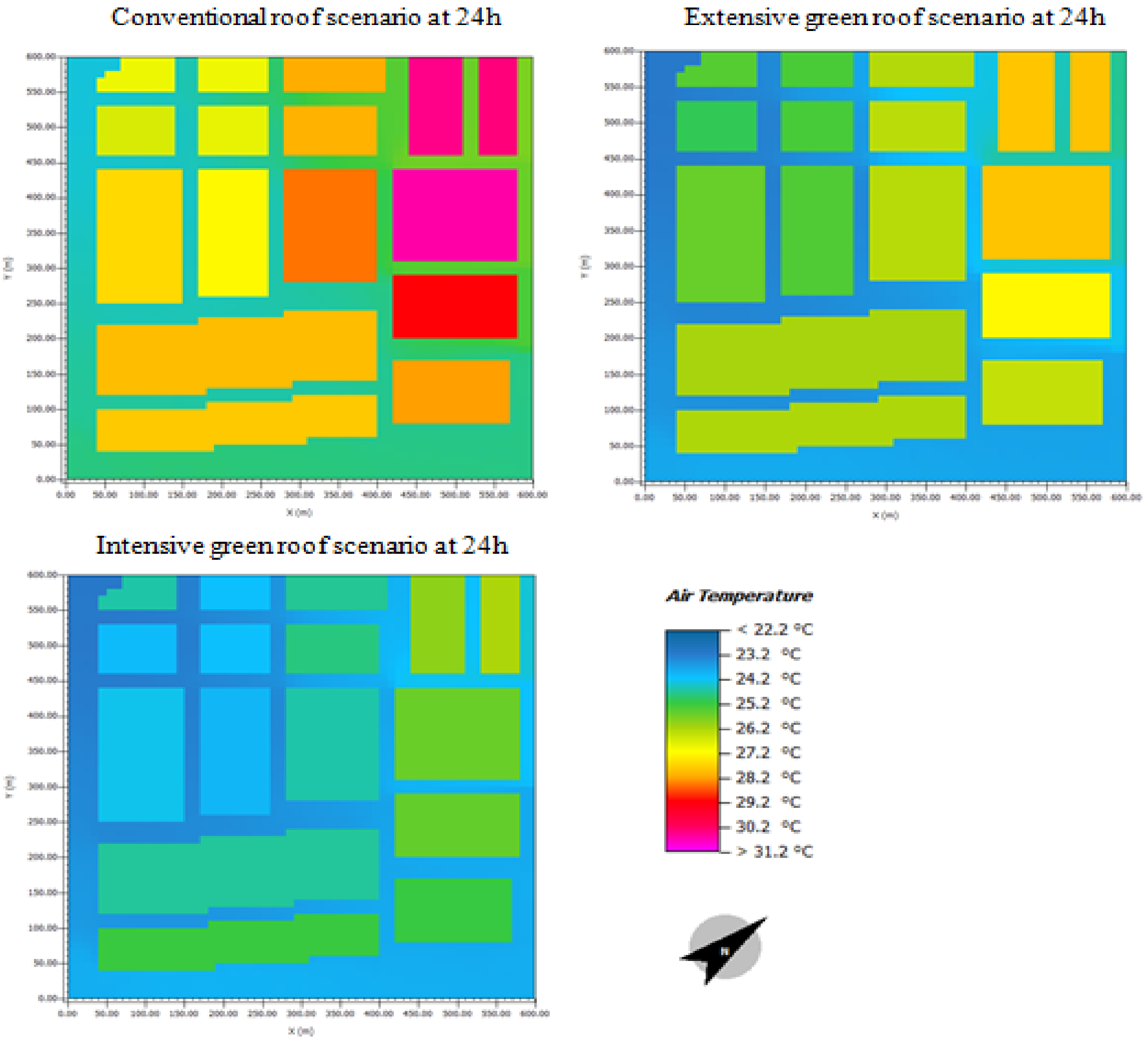


Figure 41: Air temperature at 24h, 21.12.2016 in Copacabana, Rio de Janeiro, Brazil

Source: Author

In last examined hour at 24h, the air temperature ranges from 22.2 °C to 31.2 °C with difference of 9.0 °C. The minimum air temperature of the conventional roof scenario is 24.0 °C and maximum is 31.2 °C. The minimum temperature for the extensive green roof scenario is 22.6 °C and maximum is 28.9 °C. In case of the intensive green roof scenario, the minimum air temperature is 22.2 °C and maximum is 28.1 °C. The difference in the minimum air temperature is 1.8 °C between the CRS and the IGRS. The difference in maximum air temperature is 3.1 °C between the conventional roof scenario and the intensive green roof scenario in favor of the IGRS. The urban heat island effect is usually larger at night than during day. The higher temperature effects quality of sleep and causes the necessity of utilization of air conditioners, thus causes also an increase of consumption of electricity. This can be seen in the conventional roof scenario, when the air temperature inside buildings is higher in comparison to other scenarios (Figure 41). The buildings were modeled as hollow structures assembled from the façades, roofs, and floors.

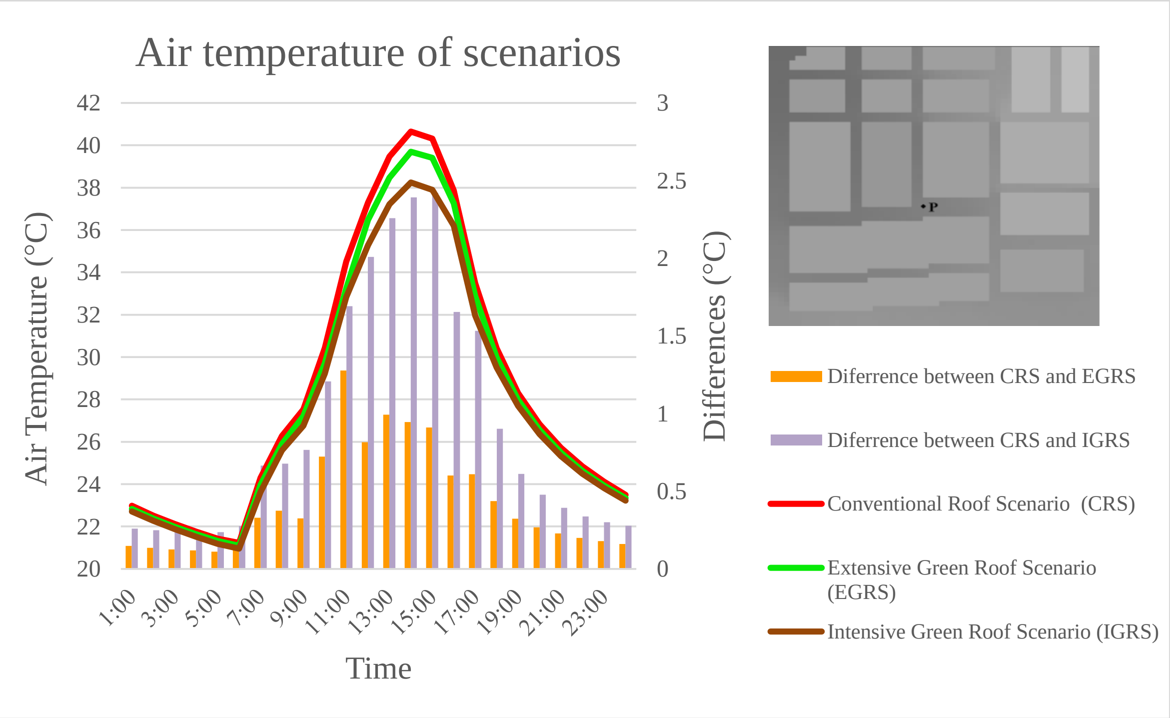


Figure 42: The receptor (P) results of scenarios, Rio de Janeiro, Brazil

Source: Author

Figure 42 is combination of a line graph and a bar graph demonstrating the comparison among three scenarios by the temperature receptor P at a height of 1.5 m above ground level in Copacabana, Rio de Janeiro, Brazil. The X axis shows hours of one day on 21st of December, 2016. The graph shows that the peak of the air temperature is reached at 15:00 with 2.42 °C difference between the conventional roof scenario and the intensive green roof scenario. The air temperatures start increasing rapidly from 7:00 until 14:00 when begin falling down. Additionally, Leonardo tool generated that the average daily air temperature of the CRS is 28.66 °C, the EGRS is 28.22 °C, and the IGRS is 27.74 °C. As a result, difference between the roof scenarios is 0.92 °C.

The difference of almost one degree Celsius is important value for Chapter 5.2 to estimate the reduction of energy demand for cooling due to installation of vegetation on existing conventional roofs.

As in case of Figure 38, the simulated air temperatures from Figure 42 could also appear to be high in comparison to real measured conditions. It can be caused by cloud free sky conditions and direct illumination of the sun of ENVI-met simulation.

The next Figures 43, 44, and 45 show the comparison among three scenarios in Parramatta district of 600 m x 600 m, Sydney, Australia in degree Celsius on 21st of December, 2016 to investigate the role of precinct scale green roofs on ameliorating the urban heat islands.

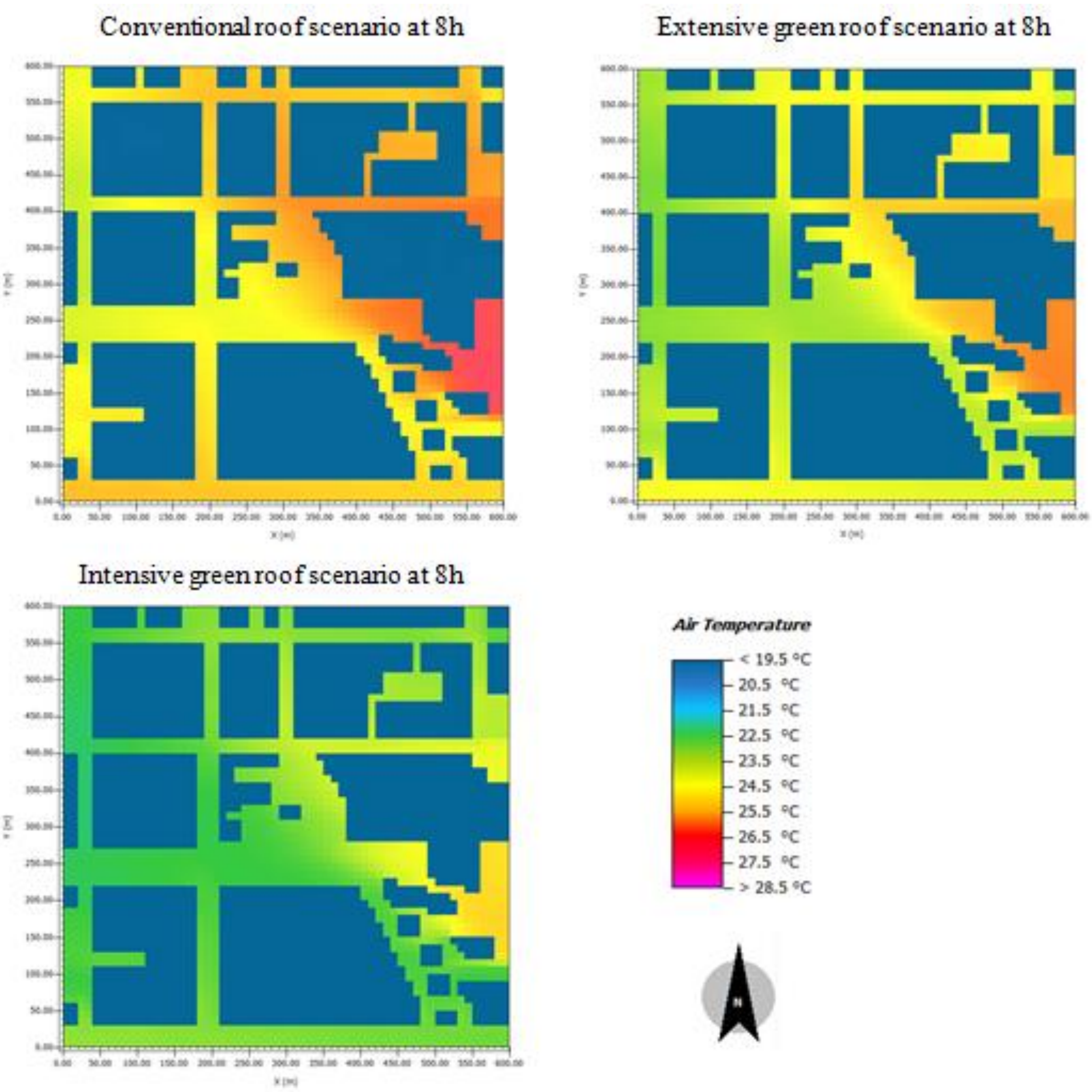


Figure 43: Air temperature at 8h, 21.12.2016 in Parramatta, Sydney, Australia

Source: Author

As can be seen in Figure 43, the air temperature at 8 am varies from 19.5 °C to 28.5 °C with difference of 11.4 °C in built-up area of 600 m x 600 m. The difference is higher than in case of Copacabana, this could be caused by morning breeze which exchanges more slowly heated air by the Sun. The highest temperature is observed on Northeast side based on the Sun's position in the morning. The simulation provides data showing that minimum temperature of the conventional roof scenario (CRS) is 20.9 °C and maximum is 28.5 °C. The minimum temperature of the extensive green roof scenario (EGRS) is 19.9 °C and maximum is 25.8 °C. For the intensive green roof scenario (IGRS), the air temperature ranges from 19.5 °C to 25.1 °C. These results demonstrate that the difference in minimum air temperature is 1.4 °C and in maximum air temperature is 3.4 °C between the conventional roof and the intensive green roof scenarios, in favor of the intensive green roof one.

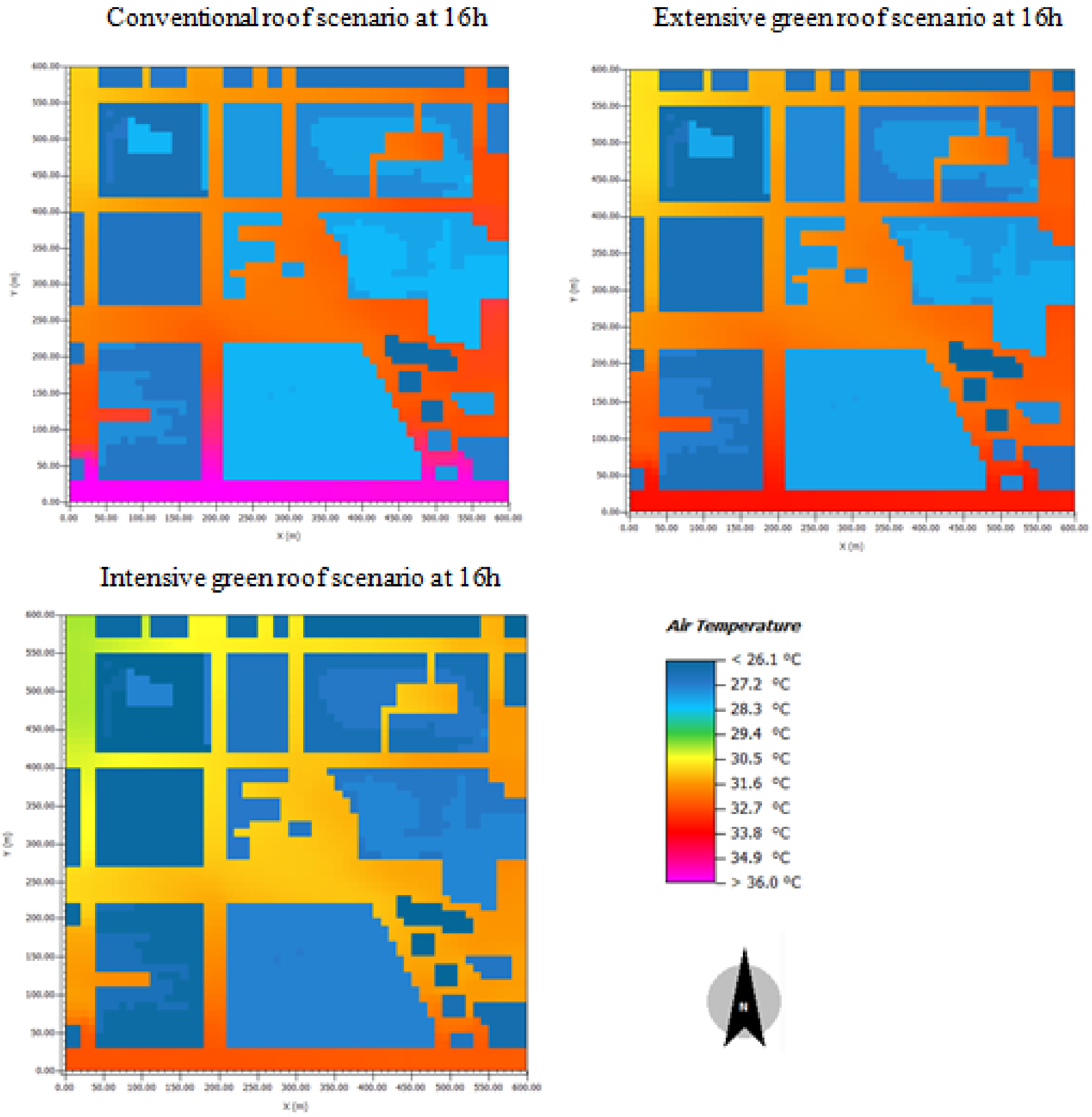
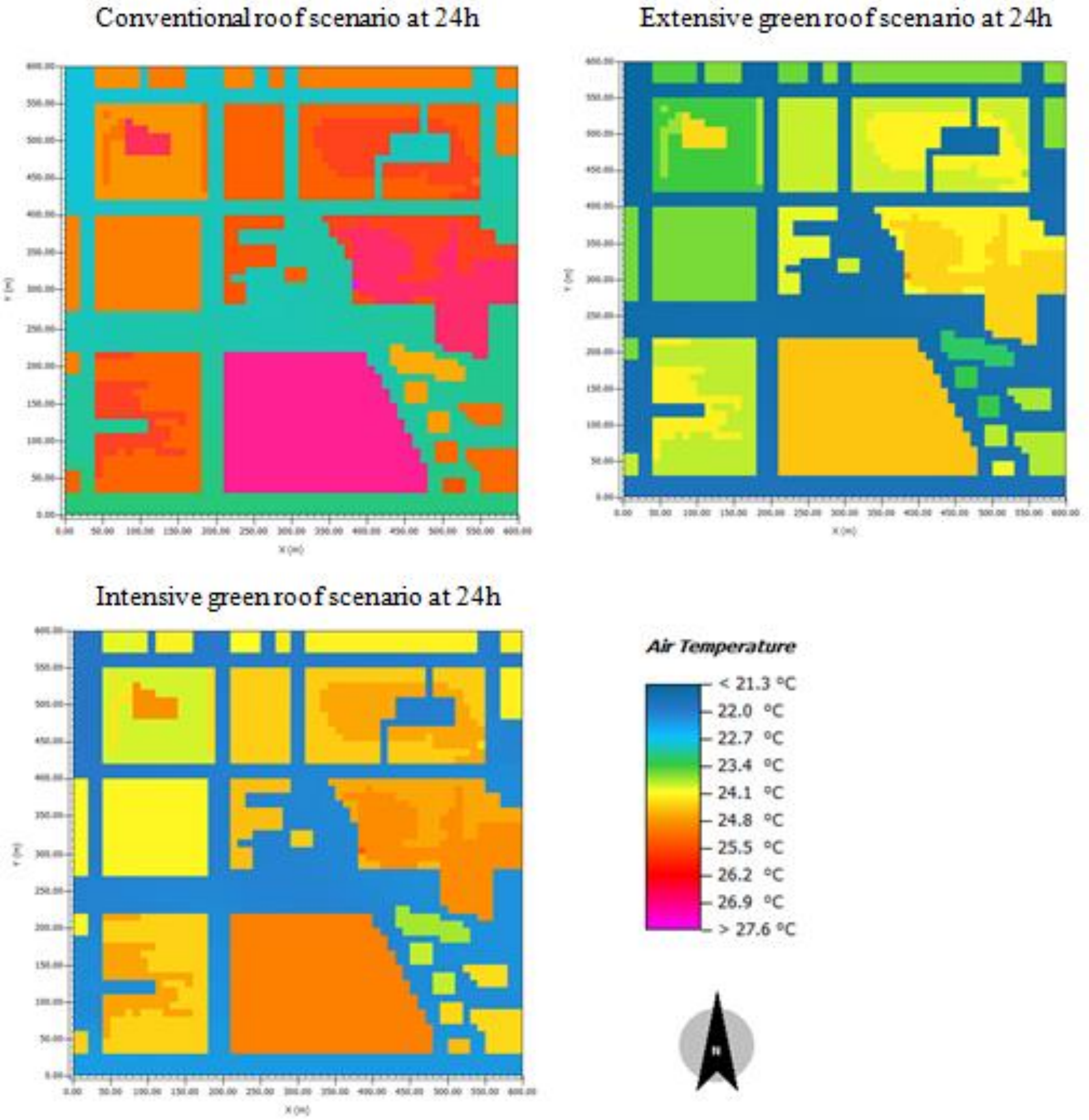


Figure 44: Air temperature at 16h, 21.12.2016 in Parramatta, Sydney, Australia

Source: Author

In Figure 44, the air temperature ranges from 26.1 °C to 36.0 °C with difference of 9.9 °C at 16h. The minimum air temperature of the conventional roof scenario is 28.9 °C and maximum 36.0 °C. The minimum air temperature of the EGRS is 26.8 °C and maximum is 32.6 °C. The air temperature of the intensive green roof scenario varies from 26.1 °C to

31.8 °C on 21st of December. These values demonstrate that the highest difference between conventional roof scenario and intensive green roof scenario in the maximum air temperature is 4.2 °C in favor of green roof. From images, it can be seen how the outdoor air temperature starts affecting the indoor air temperature of buildings which was almost same at 8h in all scenarios.


Conventional roof scenario at 24h

Extensive green roof scenario at 24h

Intensive green roof scenario at 24h

Figure 45: Air temperature at 24h, 21.12.2016 in Parramatta, Sydney, Australia
Source: Author

In last examined hour at 24h, the air temperature ranges from 21.3 °C to 27.6 °C with difference of 6.3 °C. The minimum air temperature of the CRS is 23.3 °C and maximum is 27.6 °C. The minimum temperature for the EGRS is 21.8 °C and maximum is 25.5 °C. For the IGRS, the minimum temperature is 21.3 °C and maximum is 24.9 °C. The difference in the minimum air temperature is 2.0 °C between the CRS and the IGRS. The difference in the maximum air temperature is 2.7 °C between the conventional roof scenario and the intensive green roof scenario in favor of IGRS. Given the buildings were modeled as hollow structures assembled from the façades, roofs, and floors, it can be observed from Figure 45 how the high air temperatures are trapped inside buildings during the night especially in case of conventional roof scenario. It is caused by urban fabrics which absorb surrounded warm air throughout the day (Figure 44) and store it during nighttime (Figure 45). This stored heat disturbs the thermal comfort of inhabitants and results in increasing consumption of electricity for fans and air conditioning units in order to have uninterrupted sleep by warmth (Měšťanová, et al., 2016).

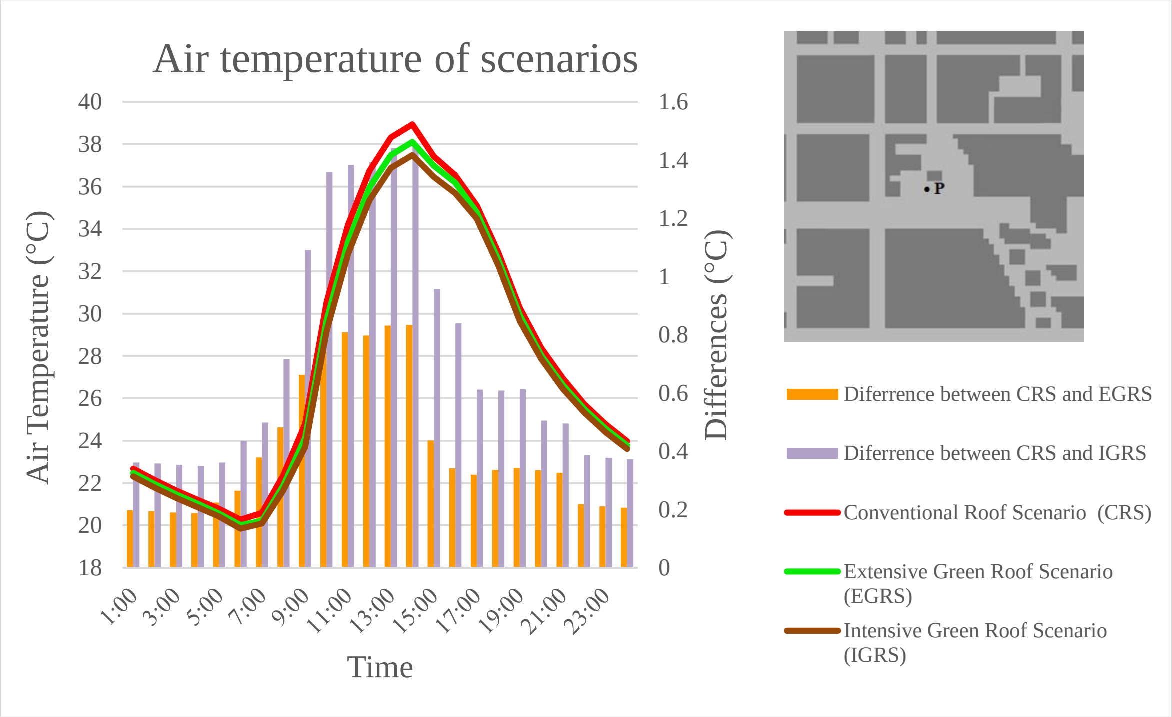


Figure 46: The receptor (P) results of scenarios, Parramatta Sydney, Australia

Source: Author

Figure 46 shows the comparison among three scenarios by the temperature receptor P at a height of 1.5 above ground level in Parramatta, Sydney, Australia. The air temperature is demonstrated by a line graph. The X axis shows hours of one day on 21st of December, 2016. The graph shows that the peak of air temperature is reached at 14:00 with 1.45 °C difference between the conventional roof scenario and the intensive green roof scenario. The air temperatures start rising sharply at 9:00 and continue until 14:00 when begin decreasing. Furthermore, it was generated from Leonardo tool that the average daily air temperature of the CRS is 28.22 °C, the EGRS is 27.80 °C, and the IGRS is 27.49 °C. Therefore, the highest difference between the roof scenarios is 0.72 °C.

The difference of 0.72 °C (almost one degree Celsius) is important value for Chapter 5.2 to estimate the reduction of energy demand for space cooling by implementation of vegetation on existing conventional roofs.

The simulated air temperatures from Figure 46 could seem to be high in comparison to real measured conditions. It can be caused by cloud free sky conditions and direct illumination of the sun of ENVI-met simulation. The air temperature of models is more affected by surface temperature of asphalt ground in build-up area. In case of measurement of the air temperature by weather station, the thermometer must be placed in the shade.

The results of ENVI-met simulation showed that the intensive green roof scenario can reduce the average daily air temperature by 0.92 °C in comparison to the conventional roof scenario in case of Rio de Janeiro on 600 m x 600 m grid during the summer. In case of Parramatta, reduction of more than half degree Celsius (0.72 °C) is achieved. In last case of Prague, decrease of 0.49 °C is reached by implementation of intensive greenery on existing roofs.

And so, the results suggest if traditional materials of roofing system are covered by vegetation, thus replaced by green roofs, it helps to reduce the urban heat island effect. Moreover, overheating problems related to high solar absorption surfaces can be further solved if the green roofs are installed instead of conventional ones to increase the sunlight reflectance and humidify the air.

6.2 ENERGY DEMAND FOR COOLING

The degree-day method is considered to be a fundamental method to estimate energy demand for space cooling. This section shows the results from BizEE software calculating cooling degree-days (Table 10).

Table 10: Cooling degree-days (CDD)

City	Latitude	Altitude (m)	CDD T_{base} 22 °C	CDD T_{base} 22.5 °C	CDD T_{base} 23 °C
Prague, Czech Republic	50°01'N	304	**123**	**107**	**94**
May			4	4	3
June			21	18	16
July			40	34	30
August			29	25	22
September			29	26	23
Rio de Janeiro, Brazil	22°54'S	10	**1582**	**1427**	**1278**
January			227	212	196
February			279	265	250
March			192	177	161
April			173	158	143
May			63	48	34
June			14	10	7
July			39	29	21
August			42	31	22
September			65	52	40
October			90	78	66
November			145	130	116
December			253	237	222
Sydney, Australia	33°86'S	90	**250**	**208**	**171**
January			74	64	54
February			32	24	17
March			13	9	7
September			11	9	8
October			12	10	9
November			17	12	8
December			91	80	68

Source: Author

Table 10 presents the summation of the number of degrees Celsius when the average temperature was above a 22 °C, 22.5 °C, and 23 °C during cooling season in 2016. These thermal thresholds correspond to uninsulated building case. The period from May to September is observed as warm period of the year for Prague. The number of CDD for 23 °C was 94 and for 22 °C was 123. The warmest month was July with the number of CDD 40 for 22 °C.

In case of Rio de Janeiro, the cooling season lasts whole year because the annual average temperature in the region varies from 22 °C to 26 °C. During examined period, there were 1582 CDD for 22 °C and 1278 CDD for 23 °C. The number of CDD is more than hundred times higher in comparison to Prague case.

The cooling period for Sydney was seven months from September (spring) to March (autumn). Sydney had twice as many cooling degree days as Prague due to warm subtropical conditions of Australia.

The calculation of energy demand for cooling in case of Prague, Rio de Janeiro, and Sydney by using Formula 4 can be seen in Table 11.

Table 11: Energy demand for cooling

City	**Correction Factor**[14]	**CDD**			**Energy needed for Cooling MWh/Y**		
		Tbase 22 °C	**Tbase 22.5 °C**	**Tbase 23 °C**	**Tbase 22 °C**	**Tbase 22.5 °C**	**Tbase 23 °C**
Prague, Czech Republic	1.2	123	107	94	0.665	0.578	0.508
Rio de Janeiro, Brazil	1.5	1582	1427	1278	10.688	9.641	8.634
Sydney, Australia	1.5	225	208	171	1.520	1.405	1.155

Source: Author

Table 11 demonstrates the energy demand for space cooling for area 100 m^2 of uninsulated building during examined period of 2016. In Prague, it was needed 0.508 MWh/Y to maintain the indoor air temperature of 23°C and 0.665 MWh/Y to keep the indoor temperature of 22°C. In Rio de Janeiro, the energy demand is much higher, 8.634 MWh/Y to maintain the indoor temperature of 23°C and 10.688 MWh/Y to maintain the indoor temperature of 22 °C. In comparison to Rio de Janeiro, the uninsulated building of 100 m^2

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[14] Correction factor – height from terrain level (effect of wind in higher floors), above 10m=1.0, 10 to 30m=1.5.

in Sydney requires less energy to maintain the indoor air temperature 22 °C, 1,520 MWh/Y. These results are used to calculate the costs to maintain specific indoor temperature.

Thereafter, input energy to convert the necessities when using electric energy is calculated by using the efficiencies for air condition energy efficiency ratio (EER) as 10[15], then when heat energy is used the efficiencies for heat exchanger for absorption chiller COP. After using Formula 5 and 6 to calculate the energy demand to cover the same necessities. The results can be seen in Table 12.

Table 12: Using electric energy to cover the necessities

City	OUTPUT			INPUT		
	[kWh]	**[BTU[16]]**	**[RT[17]]**	**[kWh]**	**[BTU]**	**[RT]**
Prague, Czech Republic **Air condition**						
Tbase 22 °C	665	2 394 000	189	227	816 354	64
Tbase 22.5 °C	578	2 080 800	164	197	709 553	56
Tbase 23 °C	508	1 828 800	144	173	623 621	49
Rio de Janeiro, Brazil **Air condition**						
Tbase 22 °C	10 688	38 476 800	3 036	3 645	13 120 589	1 035
Tbase 22.5 °C	9 641	34 707 600	2 739	3 288	11 835 292	934
Tbase 23 °C	8 634	31 082 400	2 453	2 944	10 599 098	836
Sydney, Australia **Air condition**						
Tbase 22 °C	1 520	5 472 000	432	518	1 865 952	147
Tbase 22.5 °C	1 405	5 058 000	399	479	1 724 778	136
Tbase 23 °C	1 155	4 158 000	328	394	1 417 878	112

Source: Author

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[15] The energy efficiency rating (EER) of an air conditioner is its BTU rating over its wattage. 10,000 BTU air conditioner consumes 1,000 watts, its EER is 10 (10,000 BTU/1,000 watts).

[16] BTU is the amount of heat necessary to raise the temperature of 1 pound (0.45 kilograms) of water one degree Fahrenheit (0.56 degrees Celsius). Online available: http://home.howstuffworks.com/ac5.htm

[17] Refrigeration ton (RT) is defined as the transfer of heat at the rate of 3.52 kW, which is roughly the rate of cooling obtained by melting ice at the rate of one ton per day.

Electric energy of all three cases is measured in kilowatt-hours (kWh). Table 12 shows energy demand for space cooling for all temperatures thresholds. To maintain the indoor temperature of 22 °C in summer Prague, it is necessary to consume 227 kWh of electricity. The output heat of T_{base} 22 °C is 665 kWh to cool the indoor space. In Rio de Janeiro, 3,645 kWh is needed to keep the comfort temperature of 22 °C inside building. In case of Sydney, electric energy of 518 kWh is necessary to maintain 22 °C inside the building's area of 100 m^2 during seven-months cooling period.

The input electric energy serves to calculate the costs for space cooling of uninsulated buildings. In 2016, the electricity price for households was 14.2 euro cents per kWh[18] in the Czech Republic, 52.7 Brazilian real cents[19] (12.5 euro cents per kWh) in Rio de Janeiro, 34.1 Australian dollar cents per kWh[20] (21.4 euro cents per kWh). The costs are presented in Table 13 and Figures 47, 48, and 49. These results are calculated for building's area of 100 m^2 (dtto: 4.2.1).

Table 13: Total input energy and cost

City	INPUT ENERGY Electricity [kWh]	COST [€] Electricity
Prague, Czech Republic		
Tbase 22 °C	227	32.20
Tbase 22.5 °C	197	28.00
Tbase 23 °C	173	24.60
Rio de Janeiro, Brazil		
Tbase 22 °C	3 645	455.60
Tbase 22.5 °C	3 288	411.00
Tbase 23 °C	2 944	368.00
Sydney, Australia		
Tbase 22 °C	518	110.90
Tbase 22.5 °C	479	102.50
Tbase 23 °C	394	84.30

Source: Author

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[18] Electricity prices for households, Available from: https://www.statista.com/statistics/418073/electricity-prices-for-households-in-the-czech-republic/

[19] http://www.webarcondicionado.com.br/tarifa-de-energia-eletrica-kwh-valores-e-ranking-cidades

[20] https://theconversation.com/australian-household-electricity-prices-may-be-25-higher-than-official-reports-84681

Figure 47 illustrates a bar graph showing the annual energy demand for space cooling of uninsulated building of 100 m^2 in Holešovice, Prague. The energy consumption (kWh) is shown on a green bar, with the figures being shown on the left side of the graph. The cost (€) is presented by red bar, with the figures being shown down the right side of the graph. The X axis displays three base temperature; 22 °C, 22.5 °C, and 23°C.

From Figure 47 can be seen, in case to keep the average indoor temperature of 23 °C inside buildings, the cost of electricity is 24.60 € during five-month cooling period. To maintain lower average indoor temperature of 22 °C, the cost rises up to 32.20 € for same period.

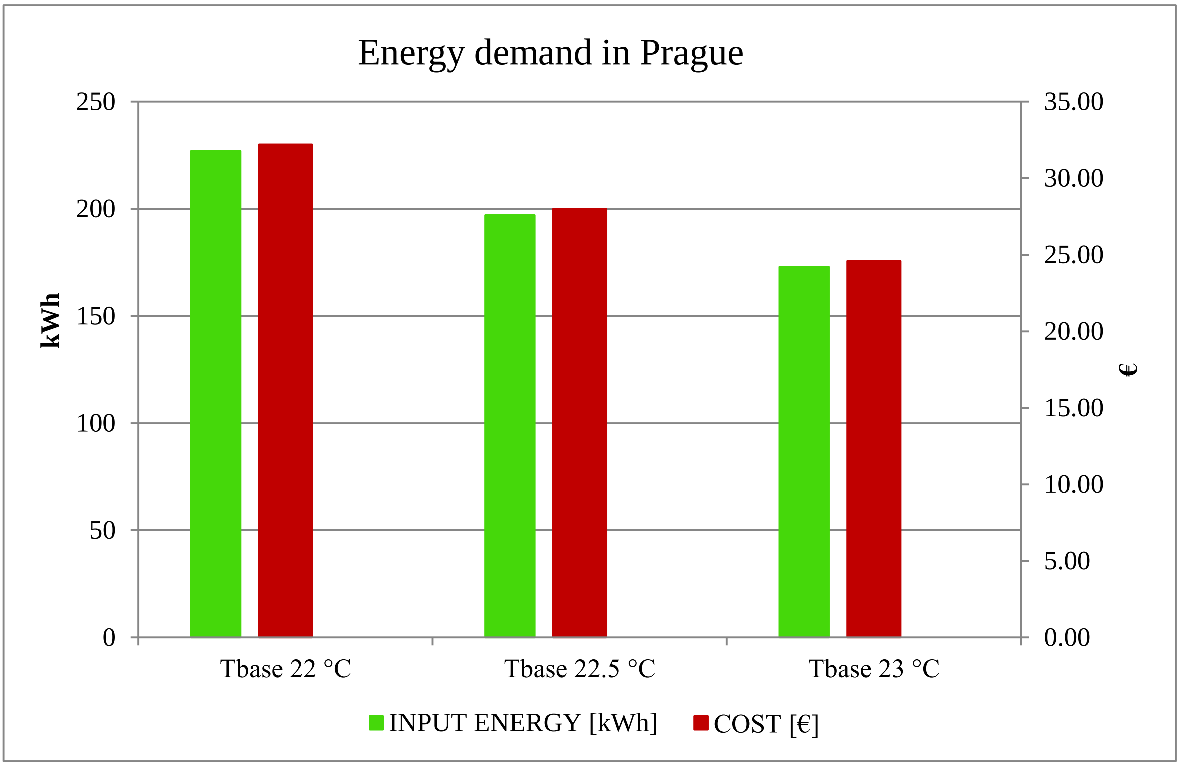

Figure 47: Energy demand in Holešovice, Prague

Source: Author

Given the results from ENVI-met simulation, the implementation of green roofs in Prague can reduce the average daily air temperature by 0.49 °C, and therefore 4.20 € can be saved annually for space cooling per unit.

Figure 48 shows the cost for space cooling in Copacabana, Rio de Janeiro during whole year 2016. It was calculated that 455.60 € is necessary to cover 3,645 kWh of electricity to keep the indoor air temperature of 22 °C inside the uninsulated building of 100 m^2 and 368.00 € for 2,944 kWh to maintain the indoor temperature of 23 °C.

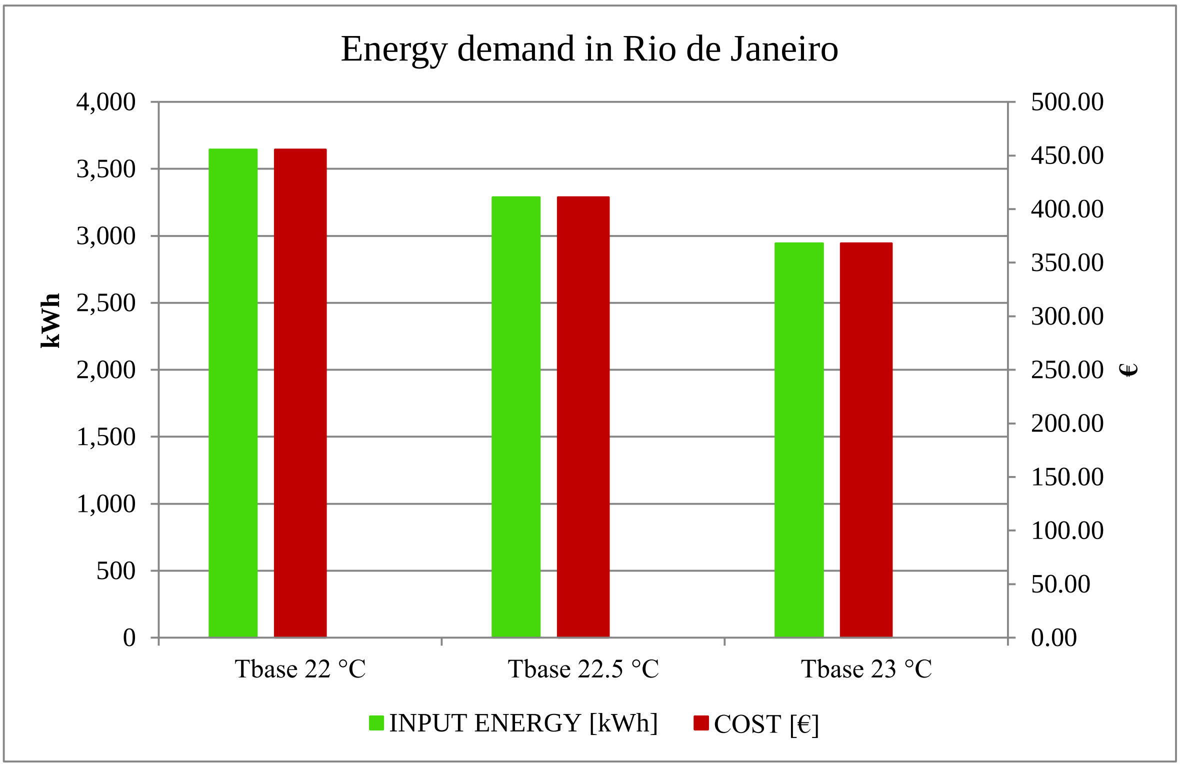

Figure 48: Energy demand in Copacabana, Rio de Janeiro

Source: Author

Considering the results from Chapter 5.1, precinct scale green roofs can decrease the air temperature by almost one degree Celsius (0.92 °C). Thus, it can saved up to 87.60 € per unit annually by installation of vegetation on existing roofs, by providing passive cooling.

As can be seen in Figure 49, the annual energy demand to maintain the indoor air temperature of 23 °C of 100 m^2 uninsulated building in Parramatta is 394 kWh, with costs of 84.30 €. The cost, to maintain the average indoor temperature of 22°C, is 110.90 € for seven-month cooling period.

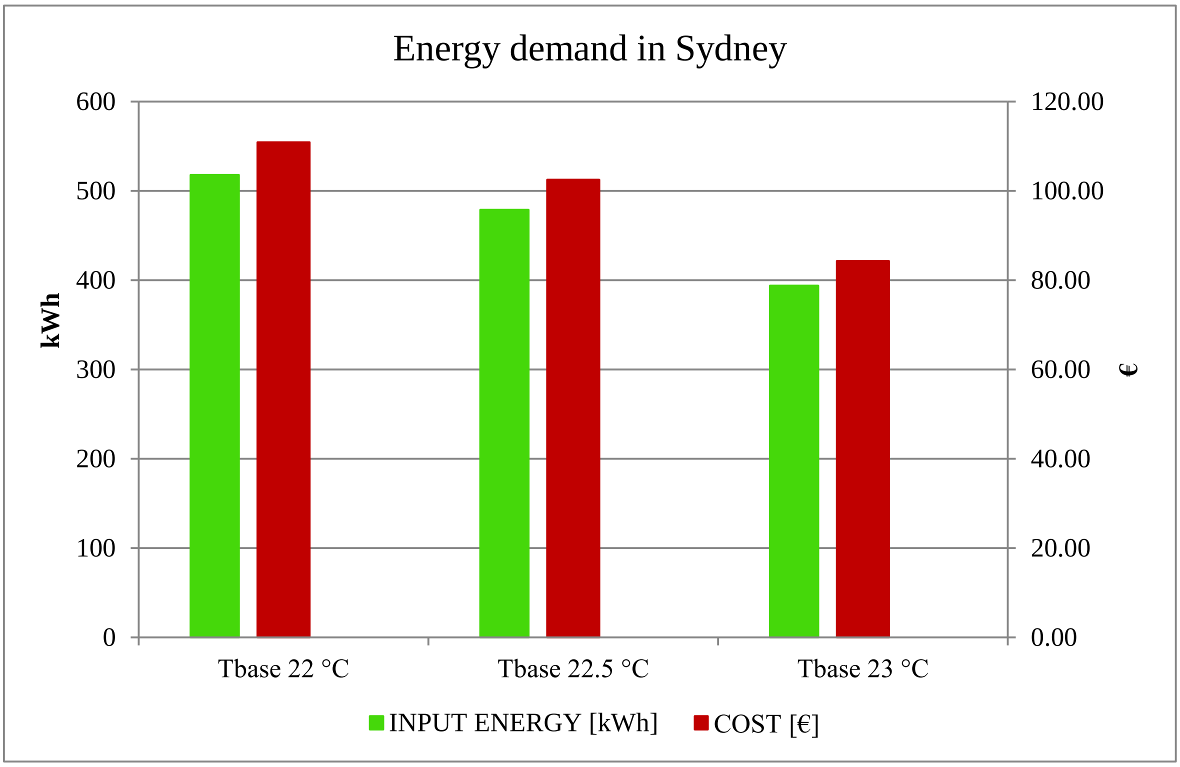

Figure 49: Energy demand in Parramatta, Sydney

Source: Author

The presented Figures 47, 48, and 49 demonstrate only the costs of energy needed to cool down the indoor air temperature of the uninsulated building of total area of $100m^2$. To be able to apply these obtained data to larger area to see major effect, the ENVI-met calculation of examined area is utilized. The ENVI-met provides information about total amount of modeled areas (Table 13). The examined area of case studies is the grid 600 x 600 m (360 000 m^2). Average building height for Holešovice district is estimated 15 m, for Copacabana district 36 m and for Parramatta 12, 26 and 38 m based on dissimilar heights of buildings.

Table 14: Geometry of the examined areas

City	Built-up area m^2	Floor area m^2	Building volume m^3
Holešovice, Prague, Czech Republic	135 400	677 000	2 031 000
Copacabana, Rio de Janeiro, Brazil	216 400	2 596 800	7 790 400
Parramatta, Sydney, Australia	254 280	1 693 520	3 4126 00

Source: Author

It can be seen in Table 14, built-up area of the selected area of Holešovice district is 135,400 m^2 from total examined area of 360,000 m^2. In case of Copacabana district, the built-up area is larger in comparison to Holešovice district with amount of 216,400 m^2. The case of Parramatta district, the built-up area is the largest among scenarios with 254 280 m^2. The highest floor area and building volume is in case of Copacabana (7,790,400) due to high-rise buildings. These urban fabrics are well visible in Figures 26, 28, and 29.

Table 15: The energy demand of the examined areas

City	INPUT ENERGY Electricity [kWh]	COST [€] Electricity
Prague, Czech Republic		
Tbase 22 °C	1 536 790	218 224
Tbase 22.5 °C	1 333 690	189 384
Tbase 23 °C	1 171 210	166 312
Rio de Janeiro, Brazil		
Tbase 22 °C	94 653 360	11 831 670
Tbase 22.5 °C	85 382 784	10 672 848
Tbase 23 °C	76 449 792	9 556 224
Sydney, Australia		
Tbase 22 °C	8 772 434	1 877 301
Tbase 22.5 °C	8 111 961	1 735 960
Tbase 23 °C	6 672 469	1 427 908

Source: Author

The values of energy demand (Tables 11, 12 and 13) are calculated based on building area of 100 m^2. To estimate the value for the total floor area of examined districts, it is necessary to calculated energy demand kWh per 1 m^2 and then multiply it.

As shown in Table 15, the cooling energy demand for the floor area of 677,000 m^2 is 1,536,790 kWh to maintain the indoor air temperature of 22 °C inside uninsulated buildings of 2,031,000 m^3 in Holešovice district. This amount of energy is estimated to cost 218,224 €. In Copacabana district, the chosen area with 2,596,800 m^2 requires 94,653,360 kWh to maintain the indoor temperature of 22 °C. The cost of 11,831,670 € is calculated to cover this energy requirement. In case of Parramatta, 8,772,434 kWh is required to maintain the indoor air temperature of 22 °C inside buildings of 3,412,600 m^3 with cost of 1,877,301 €.

Given the demonstrated results from ENVI-met simulation, implementation of vegetation on existing roofs can decrease the air temperature (almost by one degree Celsius), thus can reduce costs for space cooling. In case of Rio de Janeiro, it could be saved up 2,275,446 € per year on built-up area of 600 m x 600 m.

Twenty years ago, only a few households owned air conditioning units. Nowadays, the number of buildings, which are air conditioned, has been rising exponentially. Driven by a warmer urban areas and a rapidly expanding middle class in the world, the energy demand for space cooling is increasing all over the world. The energy demand demonstrated in Table 15 shows enormous amount of required energy for cooling only three districts of built-up area 600 m x 600 m.

In order to passively reduce excess heat in urban areas some strategies must be employed. One of them is the implementation of green roofs. From the results of Chapter 5.1 can be seen that vegetated roofs are able to reduce the air temperature almost by one degree Celsius in tropical and subtropical climate and by half degree Celsius in temperate climate. Therefore, this strategy presents one of the best possibilities how to reduce energy demand for space cooling during summer period and thus save costs for electricity.

6.2.1 Discounted payback period

In this financial part of thesis, an additional cost of an investment in installation of 100 meter squares green roof in comparison to conventional one is used to calculate the discounted payback period. The discounted payback period was selected because is more accurate than the basic payback period. The additional initial cost of green roof is calculated on subtraction of costs of green roof from costs of conventional roof (Figure 23 and 25, dtto: 2.2.6).

Given a high maintenance cost of green roof during its lifespan, energy savings due to cooling reductions are not enough high to be able to cover the additional initial investment. Therefore, it is necessary to take into consideration also subsidy program which helps to investors to implement green roofs. In case of the Czech Republic, the subsidy program New Green Savings Programme provides up to 19.50 €/m^2 (500 CZK/m^2) (NZÚ, 2017).

Based on Figure 23 and 25, the difference between cost of 100-meter square green roof and 100-meter square conventional roof is 1988.00 €. The subsidy provides 1950.00 €, thus the additional initial investment is 38.00 €. If the costs of maintenance are neglected, energy savings for cooling, which are calculated in Table 13, can be used to define the discounted payback period of the additional initial investment.

According to Table 13, in case of Prague, the energy saving was calculated to be 4.20 € per year for maintaining the indoor air temperature of 22 °C by implementation of vegetation on rooftop. Furthermore, it is important take into consideration that the electricity price will increase over the years. In the Czech Republic, Energy Regulatory Office determined average annual increase of 2.50 percent for households in next years due to inflation rate which is expected to be same (Šulová, 2017).

The additional initial investment in green roof is 38.00 € with 4.20 € annual cash flows of first year. Assuming the investor uses a discount rate of 0.75 % (Trading Economics, 2019), the discounted payback period for this investment is calculated based on the Formula 7. Due to possibility to get the subsidy in the Czech Republic, the payback period method is calculated only for Prague case study. In case of Rio de Janeiro and Sydney, until these days, there are not any subsidy, which supports the implementation of green roofs in Rio de Janeiro state and New South Wales state.

The calculation results in a discounted payback period of 8.5 years, with changing annual cash flow over the years. Figure 50 demonstrates the breakeven point at which total additional cost and economic benefit are equal, when the payback is achieved.

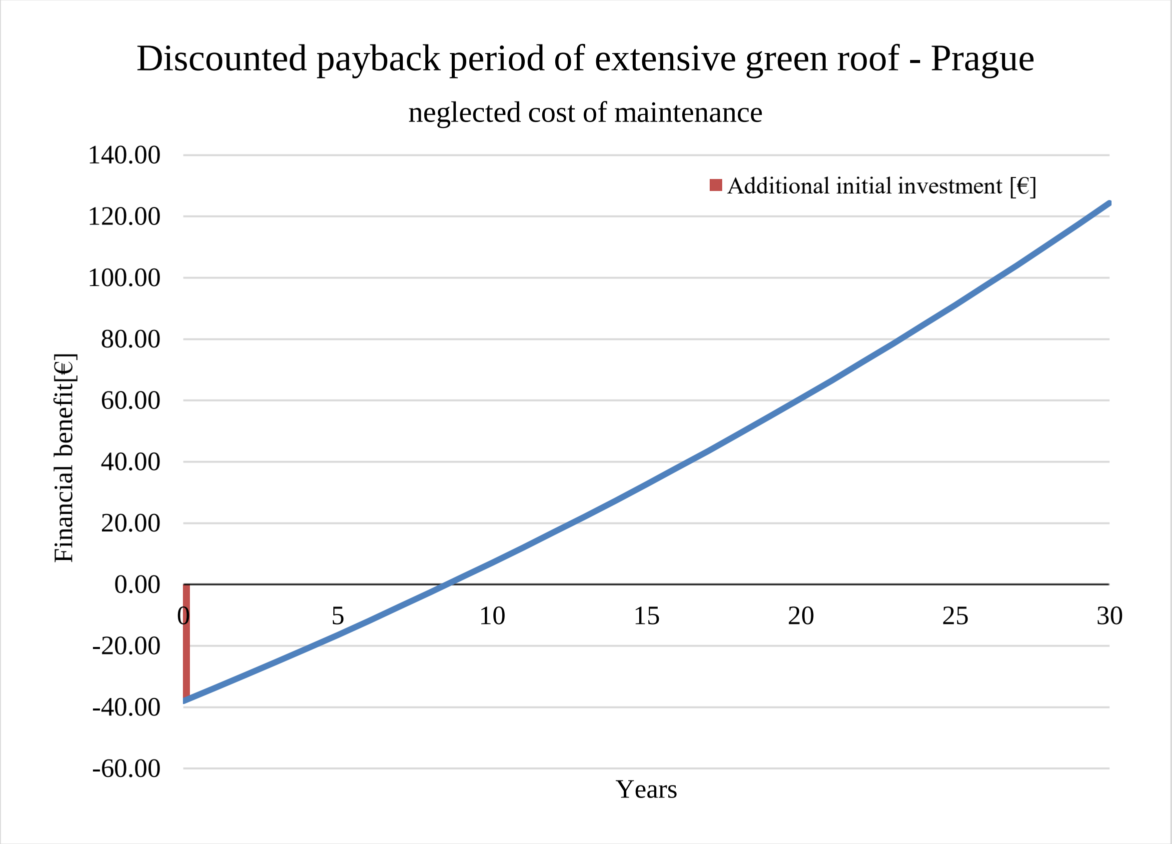

Figure 50: Discounted payback period of green roof, Prague

Source: Author

As can be seen in Figure 50, the discounted payback period of green roof is 8.5 years with regard to 38.00 € additional initial investment in the 100 meter squares green roof. This low additional investment was achieved by use of subsidy program and by neglecting of maintenance cost. According to the life cycle costing analysis of Ulubeyli et al. (2017), the lifespan for green roofs is assumed at 30 years. Therefore, if investment in a vegetated roof is paid back after nine years due to energy savings, then its implementation can be considered a profitable.

In Figure 50, the maintenance costs of green roof, which include irrigation water, replacement plants, fertilizer, weeding and pest management, are neglected. Periodic inspection and maintenance of green roof depend on the type of vegetated roof and climate. In the Czech Republic, the annual maintenance costs range from 3 to 24 €/m^2 (Czech Globe, 2017). Considering the maintenance cost of 3 €/m^2, the financial benefit in form of energy savings for space cooling is not enough high to compensate the high maintenance costs of green roof. Thus, the addition initial investment in vegetated roof is not paid back.

The obtained results demonstrate that if there is not financial funding in form of subsidy, an additional initial investment in vegetated roof can never be paid back. Therefore, the subsidy program New Green Savings Programme, which provides grants in the Czech Republic, is essential tool for investors who want to install green roof.

7 CONCLUSION

This thesis focused on the analysis of the possibility of application of green roofs as an effective tool to mitigate the urban heat island effect. This evaluation was undertaken by the consideration of excess heat in three specific urban areas with different climate condition.

The first part of thesis proposes the methodology to test the green roof mitigation strategy by using three real case studies due to evidence of the existence of the UHI. The assessment is conducted by using the results of ENVI-met, a prognostic three-dimensional microclimate simulation tool. It is described how this simulation tool can be applied and how the results can be presented. The results of simulation show that the intensive green roof scenario can reduce the average daily air temperature by 0.92 °C in summer in comparison to the conventional roof scenario, in the case of installation of greenery on existing roofs in Rio de Janeiro in built-up area of 600 m x 600 m. In case of Sydney, the difference between the intensive green roof scenario and the conventional roof scenarios is 0.79 °C. In Prague, the difference between the roof scenarios is 0.49 °C. This variance is smaller due to different geographic, climatic, and density variation.

In the second part, the living area 100 m^2 of uninsulated building is chosen as the sample to calculate the specific heat loss for one degree and calculate the energy demand for space cooling by using the cooling degree-days method. Furthermore, it is calculated quantity of input electric energy and costs by utilization of air conditioning systems. From the results of calculations, it is clear that the decrease of the air temperature, and thus the reduction of the number of cooling days leads to the reduction of use of electric power. In case of Copacabana, the implementation of green roofs on existing roofs can reduce the air temperature almost by one degree Celsius. Therefore, by passive cooling, it could be saved 2,275,446 € annually for space cooling in built-up area of 600 m x 600 m in order to maintain the indoor air temperature of 22 °C, the threshold of the comfort temperature. In case of Sydney, 449,393 € could be saved. In case of Prague, the reduction in the average daily air temperature by half a degree Celsius can provide the savings of 28,840 € per year. This part intends to demonstrate that in the matter of mitigation of urban heat island effect by the implementation of vegetated roofs, it is possible to achieve the reduction of electricity demand for space cooling.

Last part of this thesis evaluates the discounted payback period of the green roof. The additional initial cost of the vegetated roof in comparison to the conventional roof, the subsidy program, and the energy saving in cooling are used to calculate the length of time to recover from the investment. In case of neglected cost of maintenance, the discounted payback period is less than 9 years in the Czech Republic. This period is achieved also thanks to the subsidy program New Green Savings Programme, which plays important role in supporting the implementation of vegetated roofs. Otherwise, the additional investment in green roof in not paid back.

The contribution of this thesis is based on results of modeling of three case studies to demonstrate that the green roofs are effective passive tool, which decreases the air temperature, and therefore mitigates the urban heat island in temperate climate, subtropical, and tropical climate. Considering that there is not any scientific study, which is focused on precinct scale in different climate conditions, this work is unique in its field. Furthermore, the results of computer simulation confirm the accuracy of the measurements of the air temperatures, which were taken in Rio de Janeiro and are published in author’s Master thesis from UFRJ. Finally, the study demonstrates potential energy savings for space cooling due to reduction of the air temperature by installation of green roofs.

The purpose of this work is to practically help the different stakeholders to make the decision of installation of green roofs as an effective UHI mitigation strategy. Owing to positive results, this measure should be implemented internationally through legislation, urban planning, building codes and standards, incentives and education programs.

7.1 ANSWERS TO RESEARCH QUESTIONS

1. *Can precinct scale implementation of green roofs reduce the air temperature compared to conventional ones at ground level?*

Based on the received results from ENVI-met simulation, precinct scale implementation of green roofs can reduce the air temperature in summer. In case of Rio de Janeiro (tropical climate), the green roof scenario can decrease the air temperature by 0.92 °C. In Sydney (subtropical climate), the reduction in the average daily air temperature is 0.79 °C. In case of Prague (temperate climate), the precinct scale implantation of vegetated roofs can decrease the air temperature by 0.49 °C in comparison to conventional ones at ground level.

2. *What role can precinct scale implementation of green roofs have on mitigating the urban heat island effect?*

Given above mentioned reductions in the average daily air temperature by implantation of precinct scale green roofs, the urban heat island effect is mitigated and the urban air temperatures are approaching to values of the rural air temperatures.

3. *Can precinct scale adoption of green roofs reduce building energy demands for space cooling during summer period?*

Precinct scale adoption of green roofs can reduce building energy demands based on obtained results, demonstrated in Table 15. The vegetated roofs serve as passive tool to decrease the air temperature and thus reduce energy demand for space cooling. In case of Rio de Janeiro, the implementation of green roofs at the precinct scale of 600 m x 600 m can reduce 18,206,568 kWh and therefore save 2,275,446 € per year.

4. *How does an effectiveness of green roofs vary with different climatic, and density variation at precinct scale?*

Based on obtained results from precinct scale, the effectiveness of green roofs varies mostly based on climate conditions. The green roofs are the most effective in tropical climate, then in subtropical climate, and the least in temperate climate. Moreover, density variation plays also an important role. The more the urban area is built-up, the more the green roofs are effective. In very densely built-up areas, these is a lack of greenery, thus every meter square of additional vegetation has impact.

7.2 DISCUSSION

In very densely built-up areas, there is not possibility to develop parks or other green spaces as lawns, therefore, it is necessary to integrate vegetation into building envelopes in form of green roofs or green walls. The objective of this thesis was to evaluate an effectiveness of green roofs in densely built-up areas as promising measure for mitigating excess heat based on gained knowledge from the literature review. Three case studies were selected based on evidence of occurrence of the urban heat island effect, their urban density, and different climate conditions in order to demonstrate a contribution of vegetated roofs in different environment.

At the beginning, the purpose of this work was only to evaluate an effectiveness of green roofs in mitigation the UHI via computer simulation. However, when obtained results from simulation showed the possibility to reduce the air temperature by almost one degree Celsius during the summer by the implementation of green roofs, new idea of economic analysis emerged in order to calculate the reduction of energy demand for space cooling. After finding the amount of energy savings, the discounted payback period method was considered as beneficial tool for potential investor to estimate the length of time required to recover the cost of an investment in green roof.

The scale of an urban precinct was chosen to demonstrate an effect of additional vegetation in specific neighborhoods considering climate condition and current and future building morphology. Holešovice district tends to experience only horizontal urban growth, especially by replacing local brownfields, but not vertical one due to skyline of historic district of Prague. Copacabana district is already fully saturated by urban development with high-rise buildings. In case of Parramatta district, there is tendency to rise vertically. Therefore, Parramatta can suffer even more by excess heat with regard to city plans to add another residential and commercial buildings. In the coming years, Parramatta can achieve same vertical built-up level as Copacabana district.

Given increasing the percentage of the population living in urban areas, cities have been becoming denser. Along with this density come the problem of increased air temperatures creating heat islands and thermal stress, which affect health of people and increase cost for running air conditioners. The results of the selected case studies demonstrate the positive effect of green roofs on reduction of excess heat in temperate, subtropical, and tropical urban climate. Rio de Janeiro is a great example of densely built-up city suffering with heat islands in tropical climate, where the implementation of vegetated roofs on existing roofs can decrease the air temperature almost by one degree Celsius in summer. The results of all three case studies can be applied to other cities with similar climate condition and urban form. For instance, the obtained results from Rio de Janeiro can be applied to Sao Paulo.

The presented results imply that the change in local context can directly influence the urban heat island effect. The green roofs as one of the most promising measures for mitigating the UHI can play an important role in this process but this can only happen once a change in the mind-set of the political authorities, local residents, and city planners happens. Moreover, it is essential to highlight that it is expected that by mid-century people will use more energy for space cooling than space heating. And since cooling is still produced by burning fossil fuels, quantity of greenhouse gas emissions is rising, which resulting in an increase in global temperatures and environmental degradation. In order to ameliorate these negative effects, some strategies must be executed to ensure the long-term sustainability of cites. One of them is the installation of green roofs due to main benefits of vegetation.

Further research is required for developing an effective model that can take into consideration other scenarios with implementation of green walls and building morphology. Owing to increasing population density in big cities, there is rising demand for housing which has direct impact on building density and construction of high-rise buildings. As a result, the increased occurrence of heat islands and the loss of green surfaces are expected in urban environments.

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LIST OF ABBREVIATIONS

CDD	Cooling Degree Days
COP	Coefficient of Performance
CRS	Conventional Roof Scenario
CZK	Currency of the Czech Republic
EER	Energy Efficient Ratio
EGRS	Extensive Green Roof Scenario
IGRS	Intensive Green Roof Scenario
LAI	Leaf Area Index
IGRS	Intensive Green Roof Scenario
ROI	Return On Investment
RT	Refrigeration Ton
UHI	Urban Heat Island
UTC	Coordinated Universal Time

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