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Mitigating Urban Heat Island Through Green Roofs

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ABSTRACT

One of the key measures to fight urban heat island (UHI) phenomenon is by increasing the use of green approaches including green technologies and vegetation. However, there is a shortage of available space for establishing greening elements due to high density of urban development and high cost of urban land. By using green roofs, the hottest spots of a city can be mitigated. Further advantages of green roofs include mitigating air pollution, improving management of run-off water, improving public health and enhancing the aesthetic value of the urban environment. This paper reviewed, analyzed, and discussed previous literature on green roofs and their role in alleviating UHI. Previous researches acknowledged the ability of green roofs in UHI mitigation. This paper recommends using green roofs as a main strategy for decreasing the harmful impacts of UHI especially the high air temperatures as well as their ability to add to the greening of cities.

Key words: Urban heat island; green roof; air temperature; mitigation strategies; evapotranspiration.

INTRODUCTION

Rural and urban context react differently to processes of momentum transfer (air flow), energy (solar heating) and mass (precipitation). These differences are principles for unique combinations of moisture, thermal, radiative and aerodynamic properties of locations which effects how rural and urban surfaces regulate and partition existing energy (T. Oke, 1987). In turn, energy partitioning affects the thermal fluxes of these surfaces and of the surrounding layer which they are next to. (Stewart, 2011).

Many features of the physical structure of the city can give impact on the urban climate and negatively results in amplifying urban heat island intensity(T. R. Oke, 1981; P Shahmohamadi *et al.*, 2009). Heat islands form in urban and suburban areas as many traditional construction materials absorb and restore more of the solar radiation than organic materials in untouched rural areas.

But there are two key factors for this heating. Firstly, most urban building materials are impervious and waterproof, so humidity is not easily accessible to dissipate the sun's energy. Secondly, dark color materials in collaboration with canyon-like structures of urban context trap and collect more of the sun's radiative energy (Connors, Galletti, & Chow, 2013; Gartland, 2011; Prashad, 2014; Radhi, Fikry, & Sharples, 2013).

Reducing the surface temperature of roofs may play a key role in improving the thermal condition in cities facing urban heat island (Coutts, Daly, Beringer, & Tapper, 2013; K³ysik & Fortuniak, 1999; Kolokotsa, Santamouris, & Zerefos, 2013). This goal can be gained by replacement of traditional roof surfaces with green roofs offering much lower temperatures through the summer to enhance their thermal performance and reduce the absorption of solar radiation. This paper investigates the potential of green roofs in ameliorating the negative effects of UHI through the analysis of cooling process by green roofs.

Negative effects of heat islands

UHI has extensive effects on urban context and the infrastructures that support the society (P. Shahmohamadi, Che-Ani, Etessam, Maulud, & Tawil, 2011). The intensification of an urban heat island has regional-scale effects on air quality, energy demand and public health (Guo, Barnett, & Tong, 2013; Rosenzweig, Solecki, & Slosberg, 2006). UHI phenomenon intensifies the request for energy, speeding up the creation of toxic smog and producing human thermal discomfort and health troubles by increasing heat waves over metropolises (Li, Harvey, & Kendall, 2013; Synnefa, Santamouris, & Apostolakis, 2007).

Summertime UHI significantly reduces the outdoor air quality along with intensifying the energy demand of a city and as a result of this energy intensification, extensive power blackout may happens caused by the increase of the air condition usage. Reports show that thousands of people annually die as a result of heat related diseases. (Davies, Steadman, & Oreszczyn, 2008)., and the latest example is the severe overheat wave was a factor to mortality of about 50, 000 population in Europe, in August 2003. As well as the impact of electricity and temperature consumption, UHI also increases pollutant concentration over cities. Moreover, it effects the local climate by changing wind patterns, forming fog and cloud, increasing humidity, and altering the precipitation rate.” (Mirzaei & Haghighat, 2010)

Both nocturnal and diurnal UHI have a significant effect on the primary and secondary local pollutants in the environment (Sarrat, Lemonsu, Masson, & Guedalia, 2006). They can amplify the pollutant concentrations 10 times higher than the clean atmosphere (Taha, 1997). This phenomenon creates convergence and consequently transfers air pollutants to an urban area and as a result increases respiratory related illnesses in the hot center of an urban area (Lai & Cheng, 2010).

It is obvious that cities with a low climatic quality consume more electricity for cooling the buildings in summer and at the same time for lighting. Furthermore, discomfort and inconvenience for the inhabitants resulting from high temperatures is very usual (Bitan, 1992).

Mitigation Strategies

Neutralizing the impacts of UHI is a main concern for the societies. Because of the problem severity, extensive research work has been done and a large scope of literature is accessible for the subject. The available literature in this field comprises of the concepts, methodologies, latest investigation tools, latest research approaches and mitigation strategies (A. M. Rizwan, L. Y. C. Dennis, & C. Liu, 2008). A number of strategies have been suggested, consolidated and employed with noticeable outcomes (McPherson, 1994; Onishi, Cao, Ito, Shi, & Imura, 2010; A. M. Rizwan, L. Y. Dennis, & C. Liu, 2008; Arthur H Rosenfeld *et al*., 1995; Arthur H. Rosenfeld, Akbari, Romm, & Pomerantz, 1998; Mat Santamouris, Synnefa, & Karlessi, 2011; M. F. Shahidan, Jones, Gwilliam, & Salleh, 2012; Solecki *et al*., 2005; Takebayashi & Moriyama, 2007; N. H. Wong & Yu, 2005). Offered mitigation strategies and techniques include the use of green roofs (Alexandri & Jones, 2008; Bass, Krayenhoff, Martilli, Stull, & Auld, 2003; Bass, Krayenhoff, Martilli, & Stull, 2002; Kolokotsa *et al*., 2013; M Santamouris, 2012; Susca, Gaffin, & Dell’Osso, 2011; Takebayashi & Moriyama, 2007; J. K. W. Wong & Lau, 2013), the use of greenery system in the urban context including proper landscaping and design of green modules (M Santamouris, 2013; Yu & Hien, 2009; Zoulia, Santamouris, & Dimoudi, 2009), proper shading and radiation control of surfaces (Akbari, Pomerantz, & Taha, 2001), using cool roofs (Berdahl & Bretz, 1997; Bretz, Akbari, & Rosenfeld, 1998; Prado & Ferreira, 2005; Arthur H. Rosenfeld *et al*., 1998; Synnefa, Dandou, Santamouris, Tombrou, & Soulakellis, 2008; Synnefa *et al*., 2007; Takebayashi & Moriyama, 2007), mitigating of anthropogenic heat (Ichinose, Shimodozono, & Hanaki, 1999; Sailor, 2011) , Increasing the albedo of construction materials (Li, Harvey, Holland, & Kayhanian, 2013), and increasing wind velocity in order to alleviate the UHI impact in cities.

The impact of roofs on the intensification of UHI is very critical. Many researches have proven that roof surfaces are a main factor in the thermal balance of a city (Akbari, Shea Rose, & Taha, 2003; Arnfield, 1982; Bansal, Garg, & Kothari, 1992; K³ysik & Fortuniak, 1999; Susca *et al.*, 2011). Roofs include a noticeable percentage of the urban area and participate extremely to the intensification of UHI. Roofs include almost 20 to 25% of the urban surface (Akbari *et al.*, 2003; Susca *et al.*, 2011) and conventional roof materials tend to heat up in the sun to temperatures of 50–90°C. By heating roof materials some problems are created for the buildings below them such as: uprising indoor temperature, increasing energy demand for cooling, reduced indoor thermal comfort, more expenditure on utility bills, rapid corrosion of the roof materials, more deterioration on cooling systems.

Moreover hot roofs are the source of problems for their communities like increasing electricity demand particularly in summer, more probability for electrical shutdown, increasing the rate of emissions in power plants, warmer suburban and urban temperatures, aiding smog formation because of the temperature and emission combination and sending more roof materials waste sent to landfill(Gartland, 2011). Reducing the surface temperature of roofs may play a key role in improving the thermal condition in cities facing urban heat island. This goal can be gained by replacement of traditional roof surfaces with green roofs offering much lower temperatures through the summer to enhance their thermal performance and reduce the absorption of solar radiation.

Roofs and their effect on urban climate

The portion of solar radiation reflected by the exterior features of a construction extensively impacts the total heat gain or loss of the construction. This is especially true for areas that are exposed to a large amount of solar radiation (Reagan & Acklam, 1979). One of these elements is roof. Roofs cover between 20 to 25 percent of urban area and they are the hottest elements seen in thermal images of urban areas. As a matter of fact, most conventional roofing materials usually reach temperatures between 65–90ºC. Their solar reflectance extends between five and 25 percent which means they absorb 75–95 percent of the sun's radiative energy. The widespread use of traditional roofing materials in urban areas intensifies the amount of solar radiation collected by urban context. Conventional roofing materials also have other characteristics that deteriorate the heat island problem. Heat capacity and thermal conductivity are also critical issues. Traditional roofing materials tend to store more heat throughout the day, and dissipate it gradually at night.(Gartland, 2011). They emit the heat through infrared radiation and as well transfer it by convection to the volumetric air which surrounded them and exacerbate the UHI effect. As well, they conduct a part of the stored heat to the buildings below and disturb 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. Besides, the materials in traditional roofing systems are impermeable which turn them to solid elements that prevent water from penetration and latent heat evaporation process. Once latent heat phenomenon is involved, evaporation or sometimes condensation also impacts the thermal system of the roof surfaces (M Santamouris, 2013).

The process of UHI mitigation by using green roofs

Plants are one of the essential elements for a healthy city. Greenery system provides enormous benefits to an urban area which includes less energy demand, pollutant reduction, run-off water management and better ecosystem (Arabi, 2014; Gartland, 2011) . But above all, vegetation mitigates the urban heat island effect through three processes ((Akbari & Rose, 2001, 18; Emmanuel, 2005, 1600; Huang, Akbari, & Taha, 1990; Arthur H Rosenfeld *et al.*, 1995, 256; M Santamouris *et al.*, 2001, 214; M. Shahidan, 2011, 168; Shashua-Bar & Hoffman, 2000, 227; Solecki *et al.*, 2005, 39). Firstly, plants shade the buildings and protect them against solar radiation. As a result the building below them will be cooler. They reduce the heat convection to the air above, mitigate UHI and as a consequence decrease the energy for cooling. The rate of solar radiation transferred under the canopy of plants depends on plant type. But, it's usually between 6

Table 1: A summary of existing studies about the effect of green roofs on urban heat island

Researchers	Methodology	Findings
(Harazono, Teraoka, Nakase, & Ikeda, 1990) [70]	Field measurement and response factor method	The vegetation system in green roofs can be successfully applied to moderate hotter and drier climate in urbanized areas during the summer.
(Bass et al., 2002)[32]	Mesoscale Community Compressible (MC2) model with ISBA SVAT	Limited green roof coverage in an urban area was found to intensify the cooling that could be provided by similar vegetation in the core.
(Rosenzweig et al., 2006) [10]	regional climate model (MM5) in combination with observed meteorological, satellite, and GIS data	Living roofs can decrease the near surface air temperature between 0.4 and 1.3° C
(N. H. Wong et al., 2007) [71] field measurement and	Satellite imagery analysis, simulation approach	By covering 40% of Buildings in NUS university in Singapore the following results will be brought for 7th floor zone: potential reduction of 14.64–25.82% by applying turfing, of 29.96–53.67% by applying shrubs and of 31.73–56.78%
(Alexandri & Jones, 2008) [30] by applying trees.	two-dimensional, prognostic (dynamic) micro-scale model	There is an important potential of lowering urban temperatures when the building envelope is covered with vegetation.
(Hui, 2009) [72]		Green roof can reduce the increase of outdoor temperature by approximately 42%
(Chen, Ooka, Huang, & Tsuchiya, 2009) [73]	coupled simulations of conduction, radiation and convection	Installing grass roofs on medium and high rise buildings, has a negligible effect on the street level air temperature.
(Castleton, Stovin, Beck, & Davison, 2010) [74]	Review the Literature (CSCRC model)	Strong potential for green roof retrofit
(Pompeii II, 2010) [75]	Simulation through hardware scale model	green roofs do have a beneficial effect on the UHI by lowering the temperature within the city by a couple degrees in Guilford Township in Pennsylvania
(Smith & Roebber, 2011) [76]	Weather Research and Forecasting Model (ARW) coupled with an urban canopy model	Widespread adoption of vegetative rooftops, through increased albedo and

		evapotranspiration, reduces temperatures in the urban environment by as much as 3°C.
(Susca et al., 2011) [35]	Multi-scale approach: an urban and a building scale.	There is an average of 2° C difference of temperatures between the most and the least vegetated areas.
(Scherba, Sailor, Rosenstiel, & Wamser, 2011) [77]	Field experiment and energy balance models	Replacing a black roof with a white or green roof resulted in a substantial decrease in the total sensible flux on the order of 50 per cent.
(M Santamouris, 2012) [34]	Review the previous studies.	Different benefits of green roofs with focusing on mitigation of urban heat island
(Sun, Lee, Lin, & Lee, 2012) [78]	Numerical model ENVI-met and verified using field	roof greening is ineffective for human thermal comfort near the ground.
(Sun et al., 2012) [78]	Field measurement measurements.	The maximum cooling effect of green roofs on ambient air temperature in Taiwan was -1.60 °C.
(Kolokotsa et al., 2013) [33]	parametric study	green roofs can contribute considerably to theimprovement of the urban environment while simultaneously decrease the energy demand.

to 30 percent in summer and 10 to 80 percent in winter (M. F. Shahidan *et al*., 2012). Moreover, the plants with high density canopy that produce lower quantities of radiant heat will lead to the minimum quantities of soil radiation below the plant canopy. This situation improves evapotranspiration and the generation of extra latent heat supports the air temperature mitigation process and relative humidity enrichment. Reduction in air warming results in cooling benefits by creation of high quality shade and filtering the solar radiation (M. F. Shahidan *et al*., 2012). Shading plants also make people feel cooler and more comfortable. Besides, they reduce the risk of heart attack and keep the people safe from the sun's dangerous ultraviolet rays. Secondly, during the photosynthesis process, vegetation converts water, carbon dioxide and solar radiation to glucose and oxygen. For this conversion, plants use an auxiliary process named evapotranspiration to keep themselves cool (Kalogirou, 2009). Plants absorb water through their roots and release it into the air in the form of vapor through their leaves (Monteith, 1965). They use the energy of solar radiation to evaporate water and as a consequence the energy consumed for evaporation is not used to increase the air temperature. It is calculated that an average tree evaporates 1460kg of water during a clear summer day and consumes almost 860MJ of energy; this outdoor cooling effect is equivalent to five typical air conditioners (Che-Ani *et al*., 2009; Matheos Santamouris & Asimakopoulos, 2001). As a result, air temperature is lower within and downwind of well-vegetated regions because of evapotranspiration.

In overall, different studies (Huang *et al*., 1990, 7; Kurn, Bretz, Huang, & Akbari, 1994, 23) proves that peak temperatures in well vegetated areas are cooler than those in bare lands.

Thirdly, plants and greenery system can also be used as wind shield. This effect is useful throughout the cold seasons (Gartland, 2011). Experiments show that vegetation decrease wind velocity by 20–80 per cent, according to the canopy density (Huang *et al*., 1990). On the other hand, it's useful in summer too. With positioning vegetation on roofs, cooling energy needed to cool buildings will reduce and this is because the building is protected against sun radiations and reflected radiations of environment (Akbari, 2002, 119; Brown & Gillespie, 1995, 9; Robinette, 1972, 131; N. Wong *et al*., 2007, 2949; Yu & Hien, 2006, 118).

In total, most of the existing and recent studies (table below) conclude that green roofs have a strong effect in mitigation UHI and improving urban climate.

CONCLUSION

The urban environment is deteriorating annually and urban heat island phenomenon is amplifying in parallel. Increased temperature, high pollution, health problems are the negative effects of UHI. In order to ameliorate these negative effects, some strategies can be employed. One of them is the implementation of green roofs. Green roofs can be used as a multi-purpose strategy that mitigate heat island and compensate the shortage of green spaces simultaneously. Moreover, this technique leads to more positive effects such as mitigating air pollution, management of run-off water, improving public health and aesthetic aspects of an urban context. By using green roofs, the hottest spots of a city convert to the coolest ones. In a nutshell, using green roofs as a UHI mitigation strategy has the following benefits:

Reduction in cooling and heating energy demand, relying on the type of green roof, building size and climatic condition.

Apart from absorbing heat, reducing the tendency towards thermal movement of air, a green roof act as a wind buffer and filters the air moving through it;

During the photosynthesis process, greenery system converts water, carbon dioxide and sun radiation to glucose and oxygen. This cyclic process provides humans and animals food and oxygen and;

Through the evapotranspiration process plants absorb water through their roots and release it into the air in the form of vapor through their leaves. They use the energy of sun radiation to evaporate water and as a consequence the energy consumed for evaporation isn't used for increasing the air temperature.

Vegetation decrease wind velocity by 20–80 per cent, according to the canopy density and as a consequence cooling energy needed to cool buildings will reduce and this is because the building is protected against sun radiations and reflected radiations of environment. The studies investigated in this paper prove that the cooling and mitigation ability of green roofs is very important and can vastly participate in decreasing temperature in urban context. Thus, this paper recommends using green roofs not only for decreasing the harmful impacts of heat island but also for compensating the shortage of greenery system, pollutant reduction, management of run-off water and public health.

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