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# Passive and active cooling for the outdoor built environment – Analysis and assessment of the cooling potential of mitigation technologies using performance data from 220 large scale projects

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ABSTRACT

Local and global climate change increases the ambient temperature of cities by several degrees with important consequences on energy consumption, health and the economy. Advanced urban mitigation technologies contribute to decrease the ambient temperature and counterbalance the impact of urban heat islands. The present paper analyses and presents in a comparative way the mitigation potential of the known mitigation technologies using performance data from about 220 real scale urban rehabilitation projects. The average and peak temperature drop of reflective technologies, greenery, evaporative systems, earth to air heat exchangers and their combinations is calculated and presented. The mitigation potential of the main systems like cool roofs, cool pavements, green roofs, urban trees, pools and ponds, sprinklers, fountains, and evaporative towers, is analysed. It is found that the potential of the main mitigation technologies is considerable and can counterbalance UHI effects partly or fully. The average peak temperature drop calculated for all projects is close to 2 K, while the corresponding decrease of the average ambient temperature is close to 0.74 K. Almost 31% of the analysed projects resulted in a peak temperature drop below 1 K, 62% below 2 K, 82% below 3 K and 90% below 4 K.



## 1. Introduction

The urban heat island is a very well documented climatic phenomenon. It refers to the occurrence of higher ambient temperature in cities compared to the rural or suburban adjacent areas. Higher urban temperatures are the result of the positive thermal balance of cities caused mainly by the increased absorption of solar radiation and heat storage, high anthropogenic heat and reduced heat losses. Recent analyses of the published experimental data on the magnitude of the urban heat island revealed that more than 400 major cities in the world suffer from increased urban temperatures (Santamouris et al., 2015, 2016). The average urban heat island intensity may easily reach 4–5 K and in many cases may exceed 7–8 K. UHIs reflect also in subsurface UHIs (SUHI). For instance, Müller et al., 2014 measured the soil temperature at 2 m below the ground surface at eight locations in Oberhausen, Germany, and found a maximum SUHI intensity of almost 9 K. They observed that this might have an impact on the drinking water quality, as at the height of the pipelines the soil temperature was found to be greater than 20 °C.

Higher urban temperatures have a serious impact on city life and in particular on energy consumption for cooling, outdoor comfort, health and the local economy. Several studies have documented the specific consequences of local climate change on energy and peak electricity demand (Akbari et al., 2001). The peak load increases between 0.45% and 4.6% per 1 K increase of the ambient temperature above a site specific threshold, usually between 18 °C and 24 °C (Santamouris et al., 2015). Studies have shown that because of the urban heat island the cooling needs of buildings may increase up to 100%, while the peak electricity demand is increasing significantly and the efficiency of the air conditioners is decreasing considerably (Santamouris et al., 2001; Hassid et al., 2000). Moreover, the use of air conditioning additionally increases the outdoor air temperature at urban scale, even by 1–1.3 K during the night (de Munck et al., 2013; Kikegawa et al., 2003; Salamanca et al., 2014). If the external condensing units are located at each floor, thus within the urban canopy layer, rather than on the rooftops, the average urban air temperature increase due to the waste heat may get from 0.3–0.5 K to 1–1.8 K (Krpo

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et al., 2010). This sets a vicious loop that further worsens the situation for low income population and those who have no access to air conditioning.

From a global perspective, the energy penalty for cooling induced by the urban heat island is close to 0.8 kW h per unit of city surface and degree of temperature increase, or 68 kW h per person and degree (Santamouris, 2014a, 2014b). Forecasts on the future cooling demand reveal that by 2050 cooling needs of the residential and commercial sectors may increase up to 750% and 275%, respectively (Santamouris 2016b). Global forecasts of the additional peak electricity demand induced by the urban heat island indicate that it may reach a value close to 20 W per person and degree of temperature (Santamouris et al., 2015).

The increase of the ambient temperature in cities deteriorates the outdoor and indoor comfort conditions and increases the stress to vulnerable populations (Kolokotsa and Santamouris, 2015; Santamouris and Kolokotsa 2015; Santamouris 2015b). Measurements of indoor temperature in low income houses in Athens, Greece, during the very high temperature period confirm that vulnerable population is exposed to extreme temperatures for almost 85% of the heat wave period, while spells of about 200 consecutive hours above 30 °C were documented (Sakka et al., 2012). Many recent studies have documented the impact of high ambient temperatures on health. It is reported that, above a site specific threshold ambient temperature, mortality rate increases rapidly (Baccini et al. 2008), while the excess mortality above the threshold temperature in Europe, may reach 15.2% (Hajat et al., 2006). In parallel, several studies have documented the serious deterioration of the outdoor comfort conditions because of the ambient temperature increase (Pantavou et al., 2011). Finally, it is well known that high ambient temperatures in the urban environment increase the photochemical production of harmful tropospheric ozone (Stathopoulou et al., 2008), and increase considerably the ecological footprint of the cities (Santamouris et al., 2007).

Urban mitigation technologies refer to any anthropogenic intervention aiming to reduce the sources and enhance the sinks of high temperature anomalies in cities. During recent years, intensive research has been carried out to develop, test and implement at large scale, efficient urban mitigation technologies. Research has mainly been carried out in the field of reflective materials aiming to reduce absorption of solar heat by the city infrastructure; urban greenery and its optimum integration in the city structure; development of advanced evaporative systems; systems to dissipate the excess urban heat to low temperature sinks; active solar roofs, energy storage systems combined with reflective materials and solar control systems and techniques (Akbari et al., 2016). Most of the technologies are already mature and many of them are implemented in large scale urban rehabilitation projects.

Knowledge of the real cooling potential of the available mitigation technologies is indispensable information to design efficient urban climatic interventions. Accurate simulation results and experimental data from real scale applications may contribute significantly to better assess and understand the performance of the various mitigation technologies and their combination, under various boundary and climatic conditions. The available performance results have to be evaluated in a comparative and critical way in order to understand the real contribution of each of the technologies and their specific limitations. Such a comparative evaluation has been performed for the reflective and green roof technologies by Santamouris (2014a), and useful information on their pros and cons was extracted. Since then, a very high number of projects involving almost all known technologies and their combinations have been designed and implemented. For most of the projects, the detailed design information is available and, in some cases, the experimental performance is also known. The present article has collected, classified and analysed about 220 urban rehabilitation studies applied in medium and large urban zones, aiming to counterbalance the impact of urban heat island. The studies involve several passive and active mitigation systems and combinations studied and implemented under various climatic conditions. As active systems are considered those where the cooling potential is achieved through the use of mechanical system. Important information is provided regarding the interaction of the various mitigation technologies when combined together. In the following, the results of the whole analysis are presented and discussed in detail.

## 2. Evaporative techniques – Use of water in mitigating the urban heat

The use of water in reducing ambient temperature has been known for many centuries. The latent heat used to evaporate water in the atmosphere decreases the ambient temperature and may improve the thermal comfort conditions, both indoors and outdoors (Dominnguez and de la Flor, 2016). It is characteristic that the evaporation of 1 kg of water may decrease the temperature of 2000 cubic meters of water by 1 K (Dominnguez and de la Flor, 2016). In parallel, the surface temperature of the water may be several degrees lower that of the surrounding built environment and contribute to cool the ambient air through convective processes. The mitigating potential of water-based techniques has been thoroughly investigated by studies analysing the temperature patterns in cities surrounded by lakes, rivers and other water reservoirs (Xu et al., 2009; Sun and Chen, 2012; Sun et al., 2012). It is a common conclusion that urban wetlands contribute to create 'Urban Cooling Islands' resulting in a significant decrease of the urban temperature. The mitigating potential of wetlands is a function of many parameters and mainly of the wetland proximity to the city, its shape and the landscape characteristics around the water body. Analysis of existing experimental data has shown that urban wetlands may decrease the city's ambient temperature by 1–2 K (Manteghi et al., 2015).

Apart from the natural water bodies in the cities, various technologies or techniques based on the evaporation of water, are used to design and integrate urban evaporative cooling systems able to decrease the ambient temperature. A variety of passive systems like pools, ponds and fountains are widely used in public spaces for decorative and climatic reasons (Kleerekoper et al., 2012), while active or hybrid water components like evaporative wind towers, sprinklers and water courtains have been developed, installed and tested in urban public spaces around the world (Dominnguez and de la Flor, 2016).

Knowledge on the mitigating potential of water-based evaporative techniques is quite limited, and technologies and the impact of the water-based technologies is not yet thoroughly assessed. Most of the existing information is generated through simulation works while limited data are collected on real scale projects. To identify and evaluate the existing knowledge on water-based mitigation techniques, the existing published scientific information is assessed and analysed here. Eleven articles, investigating the mitigating potential in 17 case studies employing water-based technologies, have been identified and evaluated (Nishimura et al., 1998; O'Malley et al., 2015; Chadzidimitriou et al., 2013; Tumini, 2014; Taleghani et al., 2014a; Soutullo Castro et al., 2012; Velazquez et al., 1992; Dominnguez and de la Flor, 2016; Theeuwes et al., 2013; Martins et al. 2016; Amor et al., 2015). The main characteristics of the eighteen case studies as well as the reported performance are given in Table 1. Five projects refer to the mitigation potential of pools, ponds and open water bodies, three on evaporative wind towers, four on water sprinklers, two on fountains, while four projects refer to combinations of various