Solar Energy xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

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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ARTICLE INFO

Article history:
Received 13 September 2016
Received in revised form 23 November 2016
Accepted 4 December 2016
Available online xxxx

Keywords:
Passive cooling
Mitigation technologies
Urban heat island
Evaporative technologies
Urban greenery
Cool materials
Earth to air heat exchangers

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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http://dx.doi.org/10.1016/j.solener.2016.12.006
0038-092X/

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

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Table 1
Characteristics and reported performance of the water based urban mitigation projects.

No	Location of project	Theoretical or experimental study	Simulation tool	Area of project (m^2)	Area of water bodies (m^2)	Characteristics of the location	Maximum design temperature (C)	Maximum temperature decrease (C)	Mean temperature decrease (C)	Reference
Mitigation system: Pools and ponds										
1	Seagrave London, UK	Theoretical	Envi-Met	7150	700	Low Density Buildings + Open Spaces	25,6	0,4	0,1	O'Malley et al. (2015)
2	Salonica, Greece	Theoretical	Envi-Met	110,000	550	Highly Density Buildings with Open Spaces	40,9	7,1	1,9	Chadzidimitriou et al. (2013)
3	Pavones, Fontarron and Horcajo Madrid, Spain	Theoretical	Envi-Met			High Density Buildings with Open Spaces	29	2,6	1,5	Tumini (2014)
4	Portland, USA	Theoretical	Envi-Met			Urban Zone	27	1,1	0,3	Taleghani et al. (2014a)
Mitigation system: Evaporative towers										
5	Vallecas, Madrid, Spain	Experimental				Open Space	30	3,5	1,0	Soutullo Castro et al. (2012)
6	Seville, Spain	Experimental				Open Space	42	5	2	Velazquez et al. (1992)
7	Seville, Spain	Experimental				Open Space	42	7	4	Dominnguez and de la Flor (2016)
Mitigation system: Sprinklers										
8	Salonica, Greece	Theoretical	Envi-Met	11,000		Highly Density Buildings with Open Space	40,9	7,1		Chadzidimitriou et al. (2013)
9	Beirut, Lebanon	Theoretical	Manual Calculations			Open Space	35	6	4	Nunes et al. (2016)
10	Seville, EXPO 92	Experimental				Open Space	42	10	3	Dominnguez and de la Flor (2016)
12	Seville, Mairena del Alcor	Experimental				Open Space	30	7	4	Dominnguez and de la Flor (2016)
Mitigation system: Fountains										
11	Setif, Algeria	Experimental		5600	214	Open Space	35	0,9	0,9	Amor et al. (2015)
12	Osaka	Experimental				Park	35	4	1	Nishimura et al. (1998)

	Location of project	System	Theoretical or experimental study	Simulation tool	Area of project (m^2)	Area of water bodies (m^2)	Characteristics of the location	Maximum design temperature (C)	Maximum temperature decrease (C)	Mean temperature decrease (C)	Reference
Mitigation system: Other or/and Combination of the above											
13	Toulouse, France:	Pools + ponds + fountains	Theoretical	Envi-Met			Low density buildings + open space	29	6	2	Martins et al. (2016)
14	European Fictitious City	Open water body	Theoretical	WRF			Urban zone	25	1,7	0,5	Theeuwes et al. (2013)
15	Salonica, Greece	Fountains + water courtains + sprinklers	Theoretical	Envi-Met	11,000	550	Low density buildings + open spaces	40,9	7,1	1,9	Chadzidimitriou et al. (2013)
16	Setif, Algeria	Fountain + ponds	Theoretical	Envi-Met	5600	770	Open space	35	1	1	Amor et al. (2015)
17	Osaka	Falling water	Experimental				Park	35	4	1	Nishimura et al. (1998)

water based mitigation technologies such as pools, ponds, fountains, water curtains and sprinklers. Information was collected from eight monitored real scale applications, and ten from simulation studies.

Given that the performance of the case studies is evaluated under different climatic and boundary conditions, a direct comparison of the reported results is not feasible. The performance of the water-based mitigation systems is highly determined by the geometric and physical characteristics of the water system and of the considered urban area while it is strongly affected by the local climatic conditions. In particular, the humidity content in the atmosphere, ambient temperature, wind speed, turbulence and solar radiation are defining the capacity to evaporate and the mitigation potential of the water-based technologies and techniques.

Pools and ponds are the most common and well known water mitigation systems. Two specific heat transfer mechanisms

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contribute to decrease the ambient temperature: evaporation of the water through the pond surface and convective heat transfer between the ambient environment and the pond because of the low surface temperature of the water. Detailed numerical models describing the heat transfer processes in a water pond are given in Dominnguez and de la Flor, 2016. Evaporative processes depend on many parameters, however it is mainly determined by the water content of the atmosphere and its capacity to include additional water vapor. Convective processes depend on the temperature difference between the water surface and the ambient air. The temperature of the water surface is determined by the thermal balance of the pond and mainly its total thermal capacitance. Ponds with low thermal capacitance exposed to solar radiation may present a higher surface temperature than the surrounding ambient environment. The cooling effect of the pools and ponds is more apparent in the leeward space zone of the water body as cooler air is transferred from the wind. Analysis of the four case studies involving the use of water pools and ponds shows that the average decrease of the ambient temperature in the surrounding area varies between 0.1 and 1.9 K, while the maximum calculated temperature drop is between 0.4 and 7.1 K, with an average maximum value close to 2.8 K.

Fountains are equally well known passive mitigation systems used widely in traditional and modern architecture. The evaporation potential of fountains is mainly determined by the initial and final water drop radius and initial and final drop temperatures (Dominnguez and de la Flor, 2016). Experimental data from two case studies using fountains is given in Table 1. The average ambient temperature depression was in both cases close to 1 K, while the maximum temperature drop was 0.9 and 4 K in the two case studies respectively.

Sprinklers can supply water directly into the air. Evaporation takes place while the cool air is descending providing comfort. The efficiency of the system depends highly on the type and the size of nozzles, the size of the droplets, the climatic conditions in the area and in particular the wind speed and direction, humidity content and ambient temperature. Different pressures applied to the nozzles create water droplets of various size, while higher pressure helps to improve the evaporation efficiency by generating smaller droplets (Nunes et al., 2016). Use of unsuitable nozzles may generate droplets at a size that may not contribute to any significant reduction of the ambient temperature (Yamada, 2008; Yoon, 2008). A control mechanism has to be applied to avoid an excessive increase of the ambient humidity and also prevent wetting of the people because of the unevaporated droplets. The theoretical and experimental data from the four reported case studies using water sprinklers is reported in Table 1. The average temperature decrease of the ambient air was calculated between 3 and 4 K, while the maximum decrease was between 6 and 10 K. The reported temperature drop is considerably high and perhaps the highest among all the considered mitigation techniques. Unfortunately, the reported values are not validated experimentally; given the complexity of the heat transfer processes and the lack of experimental data, the accuracy of the used simulation algorithms may need further verification.

Evaporative or cooling towers may be used to cool high volumes of air. Water is sprayed in the upper part of the tower while air is induced to the tower by mechanical or natural means. Because of the evaporation the air becomes cooler and heavier and descends to the lower part of the tower and then to the ambient environment. The system is extensively studied and additional information may be found in Ford et al. (2010). The characteristics and the measured performance of the three real scale projects using towers for cooling are given in Table 1. The achieved average drop of the ambient temperature is found to vary between 1 and 4 K, while the maximum measured temperature drop ranges between 3.5 and 7 K. The specific performance data are the result of detailed experimental measurements and have to be fully trusted. However, it should be pointed out that the specific experiments were carried out in very dry urban zones where the evaporative potential is seriously increased. It is realistic to consider that such a system may present a considerably lower mitigation potential when applied in more humid climates.

A combination of the previously described systems may increase the mitigation potential of the water based evaporative systems and increase comfort. As shown in Table 1, the proposed combination of evaporative systems may decrease the average ambient temperature between 1–2 K, while the maximum decrease varies between 1 and 7.1 K. The reported range of the average and maximum temperature decreases for all the considered systems is compared in Fig. 1. Given the small size of the data set, the reported results have to be considered as preliminary indicative values. The average mitigation potential of the water based evaporative systems is close to 1.9 K, while the average maximum mitigation potential is close to 4.5 K. Analysis of the data showed a clear relation of the calculated average and maximum ambient temperature decrease with the maximum design temperature. On average, the mitigation potential of water based evaporative systems and techniques is improving with increasing ambient temperatures (Fig. 2). Higher ambient temperatures increase the saturation capacity of the air and thus the evaporative potential of the water systems. Also the convective heat transfer to the water is potentially higher given that the temperature difference between the water surface and the ambient air is increasing.

3. Use of urban green techniques and technologies

Greenery improves the urban climate and contributes to mitigate the urban heat island. Cooling of the ambient air is achieved through evapotranspiration processes, solar protection, increased radiative flow and air flow control. In parallel, trees and other greenery components filter the air, mask the noise in cities, and prevent erosion while contributing to the mental balance of urban citizens (Santamouris, 2001). Urban green spaces may be part of the city landscape, parks, street and open space greenery, or it may be integrated into the exterior envelope of buildings like green roofs and vertical green facades. Numerous studies have investigated the temperature difference between urban parks and the surrounding urban areas. It is widely agreed that urban parks develop a 'Cool Island' and present a substantially lower temperature compared to the adjacent spaces both during the day and night period (Oke et al., 1991;Spronken-Smith and Oke, 1998; Zulia et al., 2009, Skoulika et al., 2014). The magnitude of the temperature difference depends on the size and the structure of the parks, the frequency of watering, the sky obstruction and characteristics of the plantation, the density and the thermal properties of the surrounding urban zone, like the thermal capacitance, the magnitude of the released anthropogenic heat and the radiative capacity of the space, and finally, on the prevailing weather conditions (Skoulika et al., 2014). Results from existing measurements show that the night time Cool Island Intensity in parks ranges between 0.5 and 10 K, with an average value close to 1.15 K, while the day time Cool Island Intensity varies between 0.3 to 7 K with an average around 0.94 K (Skoulika et al. 2014; Bowler et al., 2010).

The important temperature difference between the park and the urban area develops a pressure difference generating an air breeze from the park to the surrounding urban zones. Several studies have attempted to identify the extent of the park's climate influence and it is widely agreed that it is mainly determined by the thermal characteristics of the surrounding urban area and in

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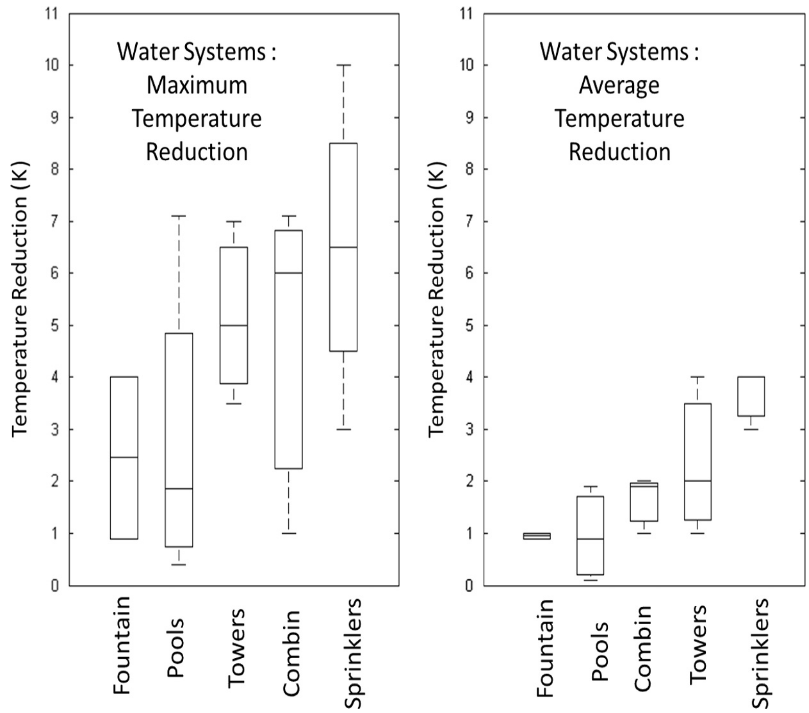

Fig. 1. Range of the average and peak temperature reduction of the water based mitigation systems and technologies.

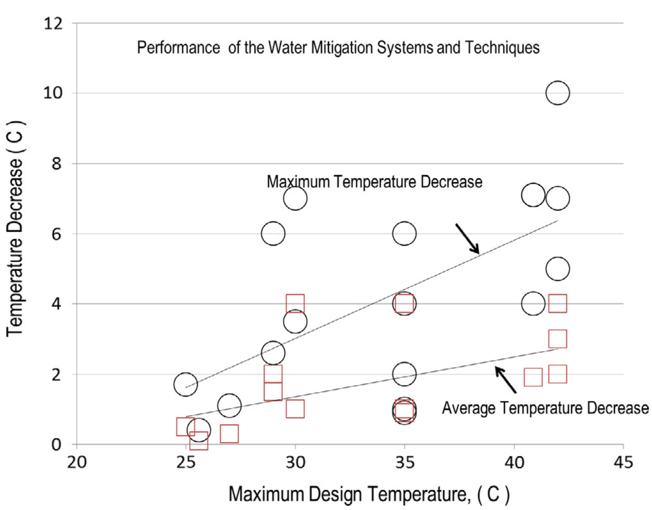

Fig. 2. Decrease of the peak and average ambient temperature for the water based mitigation systems and technologies as a function of the peak ambient temperature.

particular of the magnitude of the anthropogenic heat released (Zulia et al., 2009). Reported values vary between 200 and 2000 m beyond the park borders (Watkins et al., 2002; Wardoyo et al., 2012), while the temperature gradients beyond the park limits vary between 0.33 K per 100 m (Lindqvist 1992) and 2 K per 100 m (Lee et al., 2009).

Numerous studies have attempted to estimate the mitigation potential of various types of additional urban greenery in cities. Sixty-eight studies have been identified, analysed and evaluated. The full list and the characteristics of each study are given in Table 2. Twenty-nine articles investigated the mitigation potential of additional trees and hedges in cities, 21 articles discussed the mitigation impact of green roofs, seven studies analysed the cooling effect of grass, while 11 articles analysed the potential cooling effect of several combinations of green spaces. Two studies reported experimental results while all the rest were based on simulations. The calculated range of the maximum and average temperature drop for all the considered systems is given in Fig. 3. The potential decrease of the urban ambient temperature caused by the addition of trees and other type of greenery depends highly on the density and the properties of the considered greenery, the thermal characteristics of the city and the prevailing climatic conditions. Unfortunately, most of the above data are partially reported by the authors and a thorough comparison and analysis of the reported performance data is not possible. However, the provided information permits to extract important conclusions on the cooling potential of the various types and combinations of urban greenery and also to understand the major performance similarities and discrepancies between the considered forms of urban greenery. In particular:

(a) Addition of urban trees and hedges in cities may cause a maximum decrease of the peak ambient temperature between 0.1 K and 7 K, with a median maximum temperature drop close to 1.5 K. A high temperature drop is calculated by scenarios considering a quite extreme and almost unrealistic addition of trees in the cities. When realistic assumptions are considered, the calculated maximum temperature decrease may reach 4 K. In parallel, the calculated average temperature drop varies between zero to 3.5 K, with a median value close to 0.6 K.
(b) Green and planted roofs are excellent alternatives when important space limitations apply at the city scale and the addition of ground greenery is not possible (Karachaliou et al., 2016). The calculated maximum temperature drop of the peak ambient temperature varies between 0 and 3 K, with a median value around 0.6 K, while the average temperature drop is between 0 and 2 K, with a median close to 0.2 K. The cooling potential of the green roofs is highly affected by the LAI of the vegetation, the irrigation levels and the characteristics of the considered urban zone (Kolokotsa et al., 2013). When green roofs are applied on

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Table 2
Characteristics and reported performance of the urban greenery projects.

a/a	Location	Experimental/ theoretical	Simulation tool	Maximum design temperature (C)	Maximum decrease of the ambient temperature (C)	Average decrease of the ambient temperature (C)	Reference
Trees and hedges							
1	Paphos, Cyprus	Theoretical	Envi-Met	36	0,1	0,1	Pisello et al. (2016)
2	Rimini, Italy	Theoretical	Envi-Met	34	1,5	1,0	Pisello et al. (2016)
3	York, UK	Theoretical	Envi-Met	26	0,2	0,1	Pisello et al. (2016)
4	Grenoble, France	Theoretical	Envi-Met	34	0,1	0,1	Pisello et al. (2016)
5	Athens, Greece	Theoretical	CFD	39	3	1,5	GRBES (2016)
6	Nea Smirni, Greece	Theoretical	Envi-Met	37	6	3,5	Polyzos and Istapolou (2014)
7	Singapore	Theoretical	Envi-Met	30	3	1,5	Jusuf et al. (2006)
8	Toronto, Canada	Theoretical	Envi-Met	33	0,6	0,4	Wang et al. (2016)
10	Hania, Greece	Theoretical	Envi-Met	26	1	0,6	Tsilini et al. (2014)
11	Ho Chi Minh City, Vietnam	Theoretical	Envi-Met	28	0,5	0,3	Huynh and Eckert (2012)
12	Setif, Algeria	Theoretical	Envi-Met	35	1,3	0,3	Amor et al. (2015)
13	Vienna, Austria	Theoretical	Envi-Met	33,7	0,7	0,5	Maleki and Mahdavi (2016)
14	Campinas, Brazil	Theoretical	Envi-Met	33	5,2	3	Alchapar et al. (2016)
15	Mendoza, Argentina	Theoretical	Envi-Met	36	1,9	0,6	Alchapar et al. (2016)
16	Belgrade, Serbia	Theoretical	Envi-Met	25	2	0,8	Djukic (2015)
17	Hong Kong	Theoretical	Envi-Met	32	1,8	1	Ng et al. (2012)
18	Phoenix, USA	Theoretical	Envi-Met	33	2,4	1,1	Middel and Chhetri (2014)
19	Dubai, UAE	Theoretical	Envi-Met	48	7	2,5	Rajabi and Abu-Hijleh (2014)
20	Peristeri, Greece	Theoretical	Envi-Met	35,7	2	0,6	Ferrante (2016)
21	Hong Kong			30	1,2		Santamouris and Kolokotsa (2016)
22	Mexico City, Mexico			35	3,5		Santamouris and Kolokotsa (2016)
23	Los Angeles, USA	Theoretical	MM5	33	3	1,2	Taha (2008b)
24	Pomona, USA	Theoretical	MM5	34	1	0,3	Taha (2008b)
25	San Fernando, USA	Theoretical	MM5	34	1	0,35	Taha (2008b)
26	Toulouse, France	Theoretical	Envi-Met	29	0,5	0,2	Martins et al. (2016)
27	Manchester, UK	Theoretical	Envi-Met	26	1,5	0,6	Skelhorn et al. (2014)
28	Portland, USA	Theoretical	Envi-Met	27	1,6	0,6	Taleghani et al. (2014a)
29	Portland, USA	Experimental		27	4,7	2,8	Taleghani et al. (2014b)
30	Tokyo, Japan	Theoretical	WRF	35	0,0	0,0	Huang et al. (2009)
Green roofs							
31	Ho Chi Minh City, Vietnam	Theoretical	Envi-Met	28	0,2	0,1	Huynh and Eckert (2012)
32	Toronto, Canada	Theoretical	MC2	30	0,5	0,3	Bass et al. (2002)
33	Toronto, Canada	Theoretical	MC2	30	1,5	0,9	Bass et al. (2002)
34	California, USA	Theoretical	WRF	30	1,0	0,2	Georgescu et al. (2014a, 2014b)
35	Arizona, USA	Theoretical	WRF	35	0,8	0,1	Georgescu et al. (2014a, 2014b)
36	Texas, USA	Theoretical	WRF	34	1,4	0,3	Georgescu et al. (2014a, 2014b)
37	Mid Atlantic, USA	Theoretical	WRF	30	1,5	1,0	Georgescu et al. (2014a, 2014b)
38	Chicago,	Theoretical	WRF	25	1,8	1,0	Georgescu et al. (2014a, 2014b)
39	Tokyo, Japan	Theoretical	CFD	35	0,0	0,0	Huang et al. (2009)
40	Tokyo, Japan	Theoretical	CFD	34	1,0	0,3	(Chen et all (2009)
41	Tokyo, Japan	Theoretical	CFD	34	0,1	0,1	Chen et all (2009)
42	Chicago, USA	Theoretical	WRF	26	3,0	2,0	Smith and Roeber (2011)
43	New York, USA	Theoretical	MM5	28	0,86	0,5	Savio et al. (2006)
44	Tokyo, Japan	Theoretical	CSCRC	36	0,0	0,0	Chen et al. (2009)
45	Hong Kong	Theoretical	Envi-Met	32	0,0	0,0	Ng et al. (2012)
46	Chicago, USA	Theoretical	WRF	28	0,6	0,35	Sharma et al. (2016)
47	Melbourne, Australia	Theoretical	Envi-Met	25	1,4		Bruce and Skinner (1999)
48	Vienna, Austria	Theoretical	Envi-Met	33,5	0,3	0,2	Maleki and Mahdavi (2016)
49	Changwon City, Korea	Theoretical	Envi-Met	31	0,1	0,1	Song and Park (2015)
50	Cambera, Australia	Theoretical	LUMPS	30	0,4		Mitchell et al. (2008)
Grass							
51	Belgrade, Serbia	Theoretical	Envi-Met	25	1,4	0,5	Djukic (2015)
52	Manchester, UK	Theoretical	Envi-Met	26	0,2	0,05	Skelhorn et al. (2014)
53	Kobe, Japan	Experimental		38	0,1	0,1	Takebayashi and Moriyama (2009)
54	Dubai, UAE	Theoretical	Envi-Met	48	3,0	1,0	Rajabi and Abu-Hijleh (2014)
55	Acquila, Italy	Theoretical	Envi-Met	39	1,2	0,5	Ambrosini et al. (2014)
56	Veneto, Italy	Theoretical	Envi-Met	34	1,0	0,3	Campostrini (2013)
57	Hong Kong	Theoretical	Envi-Met	32	0,9	0,4	Ng et al. (2012)
Trees and green roofs							
58	Vienna, Austria	Theoretical	Envi-Met	33,5	1,0	0,6	Maleki and Mahdavi (2016)
59	Melbourne, Australia	Theoretical	Envi-Met	25	2,4		Bruce and Skinner (1999)
60	Dubai, UAE	Theoretical	Envi-Met	48	7,0	2,5	Rajabi and Abu-Hijleh (2014)
61	Atlanta, USA	Theoretical	WRF	32		0,38	Stone et al. (2014)
62	Philadelphia, USA	Theoretical	WRF	30		0,2	Stone et al. (2014)
63	Phoenix, USA	Theoretical	WRF	36		0,1	Stone et al. (2014)
Trees and grass							
64	London, UK	Theoretical	Envi-Met	25	0,9	0,4	O'Malley et al. (2015)
65	Phoenix, USA	Theoretical	LUMPS	35	1		Gober et al. (2010)
66	Cambera, Australia	Theoretical	LUMPS	30	0,8		Mitchell et al. (2008)
67	Dubai, UAE	Theoretical	Envi-Met	48	7,0	2,8	Rajabi and Abu-Hijleh (2014)
Grass and green roofs							
68	Dubai, UAE	Theoretical	Envi-Met	48	3,6	1,4	Rajabi and Abu-Hijleh (2014)

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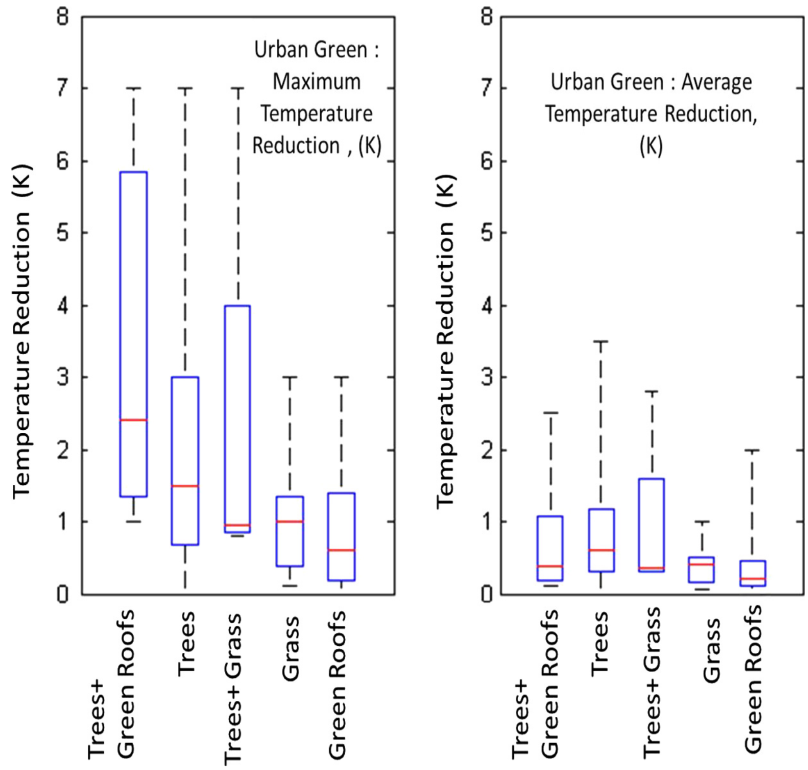

Fig. 3. Range of the average and peak temperature reduction of the urban greenery mitigation techniques.

high rise buildings, the cooling potential at street level is almost negligible. Among the 21 analysed projects, three cases concerned green roofs installed in high rise buildings where the calculated cooling potential was close to zero. Compared to the mitigation potential of urban trees, green roofs seem to present a much lower mitigation performance. Although the air temperature above the roof level may be considerably reduced because of the latent heat used by the green roof, cooler air may not reach the street level as a result of the non favourable air flow conditions above buildings.

(c) Grass is very common in open urban spaces and helps to decrease ambient temperatures. It is found that the grass may contribute to the maximum decrease of the peak ambient temperature between 0.1 and 3 K, with a median value close to 1 K. The corresponding average decrease of the ambient temperature varies between 0.1 and 1. K with a medium value close to 0.4 K

(d) Urban trees combined with green roofs seem to present the highest mitigation potential among all considered green systems. However, the size of the available projects does not permit to extract accurate figures regarding the combined mitigation potential.

4. Use of reflective materials

Increase of the albedo of cities contributes highly to mitigate urban heat island and extreme ambient temperatures (Doulos et al., 2004). Advanced materials presenting very high reflectivity in the visible or infrared, or across the whole spectrum of solar radiation together with a high emissivity value have been developed and are commercially available (Santamouris et al., 2011). Reflective materials may be used either in the envelope of buildings, cool roofs and cool facades, or in the outdoor space of cities, cool pavements. Several hundreds of studies and real applications have been carried out to identify the potential of cool roofs to decrease the cooling load of buildings. In almost all cases, well designed cool roof applications contribute to improve the environmental performance of buildings during the summer period and decrease the required energy for cooling, both in cooling and heating dominated climates (Synnefa et al., 2007, 2012; Mastrapostoli et al., 2014). On the other hand, a relatively low number of simulation studies have been performed to investigate the global mitigation potential of cool roofs in cities (Savio et al., 2006; Synnefa et al., 2008).

Cool pavement technologies have benefited from important recent technological developments and have gained increasing acceptance. Several technologies of reflective pavements have been proposed while their urban heat island mitigation capacity has been assessed using theoretical and experimental methods (Santamouris, 2013). A full review of the existing as well as the proposed innovative pavement technologies is given in Santamouris (2016c). A significant number of real scale applications using advanced cool pavement technologies has been realized and experimental monitoring has shown that cool pavement technologies can reduce significantly the ambient urban temperature, improve outdoor comfort levels and protect the health of vulnerable populations (Santamouris et al., 2012a; Fintikakis et al., 2011; Gaitani et al. 2011).

Several simulation studies have been performed aiming to investigate the mitigation potential of the global albedo increase in cities (Sailor 1995; Rosenfeld et al., 1995; Rosenfeld et al., 1998; Millstein and Menon, 2011; Sailor et al., 2002; Zhou et al., 2010; Taha, 2008a; Lynn et al., 2009). Authors consider the use of cool roofs, cool facades and reflective pavements. All the previous studies have been analysed in detail and specific correlations between the average albedo increase and the mean and peak temperature reductions have been proposed (Santamouris, 2010).

The significant developments in terms of commercially available reflective materials, the availability of accurate and easily

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available simulation tools as well as the increasing acceptance of the reflective mitigation technologies has resulted in the design and construction of many real scale projects aiming to mitigate the urban heat island intensity using reflective materials. Unfortunately, most of the projects are not experimentally monitored and detailed information is not always available. Also, most of the simulation studies are not published and results from only a few of them are available to the scientific community. Despite these problems, almost 75 experimental and simulation studies concerning the application of cool roofs, cool pavements or a combination of them are identified and analysed. The specific data regarding the albedo increase, as well as the calculated or measured average and maximum temperature increase, are given in Table 3. Twenty-four projects analyse the global mitigation potential of cool roofs in cities, 15 projects refer to the mitigation potential of cool pavements while the rest refer to the combined use of cool roofs and pavements. The increase of the albedo for each case study was calculated using the specific maps and the other information provided with each article. To avoid major inaccuracies, Table 3 provides a range of possible albedo increase and not a crisp value.

The reported results from each considered case study have been analysed in detail and the range of the estimated drop of temperature for each technology is calculated. Fig. 4 provides the range of the average and the maximum temperature drop at ground level for each of the three considered technologies. The median of the peak temperature drop achieved when cool roof technologies are used is close to 1 K, increasing up to 1.3 K for the cool pavements and 1.43 K for the combination of cool roofs and pavements. The absolute maximum temperature drop is 2.3 K for the cool roofs, 2.5 K for the cool pavements and 3.4 K for their combination. The median of the average temperature drop is calculated between 0.3 and 0.4 K for all considered technologies, while the maximum of the average decrease is close to 1 K. Based on the above, the following conclusions may be drawn:

(a) Cool pavements seem to present a higher mitigation potential than cool roofs. Cool pavements are located at ground level and decrease the ambient temperature at that level through convection processes. On the contrary, reflective roofs are located at a certain distance from the ground and cool the air above the roof. Their cooling potential at ground level depends on the capacity of the cool air to reach ground level. The taller the building the less the cooling potential of cool roofs. Simulations performed for urban zones involving high rise buildings like Hong Kong and Tokyo, have shown that the cooling contribution of cool roofs is almost negligible under these conditions.
(b) The combination of cool roofs and cool pavements presents a higher cooling capacity than each of the two technologies separately, but much lower than if they were simply added together. The final mitigation impact depends strongly on the total surface of the cool materials installed, and depends on the thermal balance of each installed system. Both technologies usually operate under very similar surface temperatures, have an almost similar sensible heat release and may decrease the ambient temperature at about the same temperature levels. When combined, the impact of each technology on the surface temperature of the other is quite reduced, limited to the additional increase/decrease of the ambient temperature affecting the convection gains/losses. As a matter of fact, the temperature difference between the ambient air and the surface of each technology is not highly affected.
(c) Based on the performance data from a much smaller data set of case studies, a previous article has proposed an almost linear relation between the average and the maximum temperature drop and the corresponding increase of the albedo (Santamouris, 2014b). Because of the limited availability of data, the correlation was based on data from all types of reflective technologies. Using the performance data from the 74 case studies, a similar analysis has been performed for each of the two reflective technologies, their combination and the whole data set. The corresponding plots for the maximum and the average temperature drop as well as the calculated linear correlations are given in Figs. 5 and 6 respectively. When all data are included, the estimated relation between the average and maximum temperature drop and the albedo increase are somewhat lower but in the same order of magnitude to the ones proposed by Santamouris (2014b). In particular, the estimated decrease of the average and maximum temperature drop per 10% increase of the albedo is calculated by the present study close to 0.27 K and 0.78 K while in the previous work it was 0.31 K and 0.9 K respectively. With respect to the specific technologies, it is found that the average and maximum temperature drops per 10% increase of the albedo are 0.23 K and 0.62 K for the cool roofs, 0.27 K and 0.94 K for the cool pavements and 0.35 K and 0.91 K for their combination. The maximum calculated temperature drop for the combination of cool roofs and pavements is slightly lower that the one given for the cool pavements. This is because the data available for the combination of the two technologies is quite limited.
(d) All performance data presented in Table 4 results from simulation studies. Unfortunately, experimental data on the mitigation potential of large scale application projects involving cool roofs or combination of cool roofs and pavements, are not available. However, simulation as well as monitored performance data from four projects involving the use of various types of cool pavements is available (Projects 26, 27, 35 and 38 of Table 3). Both simulation and experimental data are calibrated under the same ambient climatic conditions using the methodology described by Santamouris et al. (2012a). The range of the calibrated simulation and experimental performance is given in Fig. 7. As shown, the experimental performance is almost 16% lower than the simulated one. While the predicted average maximum temperature drop per 10% of the albedo increase was close to 0.8 K, the experimentally achieved drop was around to 0.67 K. This is mainly due to the ageing caused by the deposition of rubber from the tyres of cars on the surface of cool asphaltic materials just after their installation (Synnefa et al., 2011) and also to the decrease of the reflectivity of the cool pavements because of the deposition of several atmospheric pollutants on their surface (Mastrapostoli et al., 2016).

5. Use of ground cooling techniques – Earth to air heat exchangers

The use of a ground as a heat sink to dissipate excess heat is extensively used to cool buildings (Santamouris et al., 1995). Earth to air heat exchange is the most popular system among the various ground cooling techniques. The system involves horizontal tubes placed at a certain depth in the ground where the ambient air is circulated using fans. Because of the substantial temperature difference between the ambient air and the ground at the specific depth, heat is dissipated to the ground and the temperature of the circulated air is significantly reduced. The air from the exchangers is then distributed to the outdoor environment to decrease the ambient temperature and provide comfort to the pedestrians. The performance of the earth to air heat exchangers depends on many parameters like the geometric and thermal char-

Table 3
Characteristics and reported performance for all projects using reflective materials.

No	Location	Increase of the albedo in the study area (0–1)	Design temperature (C)	Maximum temperature reduction (C)	Average temperature reduction (C)	Experimental/Si	Simulation tool used	Reference
Cool roofs								
1	Rimini, Italy	0,05–0,15	35,5	0,9	0,21	Simulation	Envi-Met	Pisello et al. (2016)
2	Toronto, Canada	0,05–0,15	33	0,7	0,17	Simulation	Envi-Met	Wang et al. (2016)
3	Ho Chi Minh City, Vietnam	0,03–0,07	28	0,1	0,1	Simulation	Envi-Met	Huynh and Eckert (2012)
4	Vienna, Austria	0,2–0,3	33,5	0,5	0,35	Simulation	Envi-Met	Maleki and Mahdavi (2016)
5	Colombo, Sri Lanka	0,15–0,25	30	1,2	0,5	Simulation	Envi-Met	Emmanuel et al. (2007)
6	Athens, Greece	0,3–0,4	35,3	2,2	1	Simulation	MM5	Synnefa et al. (2008)
7	Athens, Greece	0,1–0,2	35,3	1,5	0,43	Simulation	MM5	Synnefa et al. (2008)
8	Changwon City, Korea	0,03–0,08	31	0,2	0,1	Simulation	Envi-Met	Song and Park (2015)
9	Phoenix, USA	0,05–0,15	33	0,6	0,3	Simulation	Envi-Met	Middel and Chhetri (2014)
10	Phoenix, USA	0,15–0,25	33	1,5	0,6	Simulation	WRF	Georgescu et al. (2012)
11	Aquila, Italy	0,2–0,3	39	1,8	0,5	Simulation	Envi-Met	Ambrosini et al. (2014)
12	New York, USA	0,05–0,15	31	0,31	0,25	Simulation	MM5	Lynn et al. (2009)
13	Phoenix, USA	0,1–0,2	35	1		Simulation	LUMPS	Gober et al. (2009)
14	Toulouse, France	0,10–0,15	29	0,9	0,4	Simulation	Envi-Met	Martins et al. (2016)
15	California, USA	0,15–0,25	30	1,85	0,7	Simulation	WRF	Georgescu et al. (2014a, 2014b)
16	Arizona, USA	0,15–0,25	35	1	0,5	Simulation	WRF	Georgescu et al. (2014a, 2014b)
17	Texas, USA	0,2–0,3	34	2	0,5	Simulation	WRF	Georgescu et al. (2014a, 2014b)
18	Florida, USA	0,05–0,15	33	0,7	0,3	Simulation	WRF	Georgescu et al. (2014a, 2014b)
19	Mid Atlantic, USA	0,25–0,35	30	2,3	0,7	Simulation	WRF	Georgescu et al. (2014a, 2014b)
20	Chicago	0,25–0,35	25	2,2	0,6	Simulation	WRF	Georgescu et al. (2014a, 2014b)
21	Tokyo, Japan	0,10–0,15	35	0,4	0,1	Simulation	CFD	Huang et al. (2009)
22	Atlanta, USA	0,10–0,20	32		0,18	Simulation	WRF	Stone et al. (2014)
23	Philadelphia	0,10–0,20	30		0,16	Simulation	WRF	Stone et al. (2014)
24	Phoenix	0,10–0,20	36		0195	Simulation	WRF	Stone et al. (2014)
Pavements								
25	Western Athens, Greece	0,15–0,25	36	2,5	1	Simulation	CFD	GRBES (2016)
26	Historical Center, Athens, Greece	0,15–0,20	37	1,8	0,45	Simulation and experimental	CFD	GRBES (2016)
27	Aegaleo, Athens, Greece	0,15–0,25	35	1,3	0,4	Simulation and experimental	Envi-Met	Kyriakodis et al. (2016)
28	Athens, Greece	0,15–0,25	29	1	0,42	Simulation and experimental	CFD	Georgakis et al. (2014)
29	Toronto, Canada	0,03–0,08	33	0,5	0,12	Simulation	Envi-Met	Wang et al. (2016)
30	London, UK	0,05–0,15	25	0,5	0,2	Simulation	Envi-Met	O'Malley et al. (2015)
31	Ho Chi Minh City, Vietnam	0,03–0,07	28	0,2	0,1	Simulation	Envi-Met	Huynh and Eckert (2012)
32	Agia Paraskevi, Athens, Greece	0,05–0,15	29	0,8	0,2	Simulation	Envi-Met	GRBES (2016)
33	Ilioupolis, Athens, Greece	0,15–0,25	37,5	1,4	0,4	Simulation	CFD	GRBES (2016)
34	Suburban Thessaloniki, Greece	0,15–0,25	36	1,3	0,34	Simulation and experimental	Envi-Met	Papadopoulos (2016)
35	Marousi, Greece	0,2–0,3	34	1,9	0,7	Simulation and experimental	Envi-Met	GRBES (2016)
36	Veneto, Italy	0,15–0,25	34	2,2	0,6	Simulation	Envi-Met	Campostrini (2013)
37	Madrid, Spain	0,05–0,15	29	1	0,3	Simulation	Envi-Met	Tumini (2014)
38	Agia Paraskevi2, Athens, Athens	0,05–0,1	34	1,8	0,36	Simulation and experimental	CFD	GRBES (2016)
39	Florina, Greece	0,05–0,15	35	1,4	0,3	Simulation	CFD	Zoras et al. (2014)

(*continued on next page*)

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Table 3 (*continued*)

No	Location	Increase of the albedo in the study area (0–1)	Design temperature (C)	Maximum temperature reduction (C)	Average temperature reduction (C)	Experimental/Si	Simulation tool used	Reference
Cool roofs and cool pavements								
40	Los Angeles, USA	0,05–0,15	33	1	0,46	Simulation	MM5	Taha (2008b)
41	Los Angeles, USA	0,15–0,25	33	2,1	0,9	Simulation	MM5	Taha (2008b)
42	Pomona, USA	0,05–0,15	34	1,1	0,45	Simulation	MM5	Taha (2008b)
43	Pomona, USA	0,15–0,25	34	2,1	0,75	Simulation	MM5	Taha (2008b)
44	San Fernando, USA	0,15–0,25	34	2	0,9	Simulation	MM5	Taha (2008b)
45	San Fernando, USA	0,15–0,25	34	1,5	0,7	Simulation	MM5	Taha (2008b)
46	Atlanta, USA	0,15–0,25	32		0,23	Simulation	WRF	Stone et al. (2014)
47	Philadelphia, USA	0,15–0,25	30		0,35	Simulation	WRF	Stone et al. (2014)
48	Phoenix, USA	0,15–0,25	36		0,16	Simulation	WRF	Stone et al. (2014)
49	Colombo, Sri Lanka	0,05–0,15	30	0,2	0,16	Simulation	Envi-Met	Emmanuel et al. (2007)
50	Campinas, Brazil	0,10–0,20	33	1,3	0,45	Simulation	Envi-Met	Alchapar et al. (2016)
51	Mentoza, Argentina	0,10–0,20	36	0,7	0,3	Simulation	Envi-Met	Alchapar et al. (2016)
52	Grenoble, France	0,05–0,15	34	0,3	0,2	Simulation	Envi-Met	Pisello et al. (2016)
53	New York, USA	0,10–0,20	31	0,62	0,4	Simulation	MM5	Savio et al. (2006)
54	Los Angeles, USA	0,05–0,10	32	1,4	0,6	Simulation	Colorado State University Mesoscale Model	Sailor (1995)
55	Los Angeles, USA	0,10–0,20	32	3	0,5	Simulation	Colorado State University Mesoscale Model	Rosenfeld et al. (1995)
56	Los Angeles, USA	0,10–0,20	32	1,5	0,3	Simulation	Colorado State University Mesoscale Model	Rosenfeld et al. (1998)
57	Colombus, USA	0,01–0,05	26		0,1	Simulation	WRF	Millstein and Menon (2011
58	San Antonio, USA	0,01–0,05	33		0,14	Simulation	WRF	Millstein and Menon (2011)
59	San Diego, USA	0,01–0,05	37		0,13	Simulation	WRF	Millstein and Menon (2011)
60	Jacksonville, USA	0,01–0,05	30		0,12	Simulation	WRF	Millstein and Menon (2011)
61	San Jose, USA	0,01–0,05	33		0,23	Simulation	WRF	Millstein and Menon (2011)
62	Dallas, USA	0,03–0,07	34		0,20	Simulation	WRF	Millstein and Menon (2011)
63	Phoenix, USA	0,03–0,07	35		0,16	Simulation	WRF	Millstein and Menon (2011)
64	Miami, USA	0,04–0,08	34		0,20	Simulation	WRF	Millstein and Menon (2011)
65	Chicago, USA	0,05–0,1	26		0,27	Simulation	WRF	Millstein and Menon (2011)
66	Atlanta, USA	0,05–0,1	30		0,14	Simulation	WRF	Millstein and Menon (2011)
67	Philadelphia, USA	0,07–0,12	28		0,24	Simulation	WRF	Millstein and Menon (2011)
68	Houston, USA	0,05–0,15	30		0,19	Simulation	WRF	Millstein and Menon (2011)
69	New York, USA	0,05–0,15	28		0,35	Simulation	WRF	Millstein and Menon (2011)
70	Dedroid, USA	0,1–0,15	25		0,39	Simulation	WRF	Millstein and Menon (2011)
71	Los Angeles, USA	0,1–0,15	33		0,53	Simulation	WRF	Millstein and Menon (2011)
72	Philadelphia, USA	0,05–0,15	28	0,5	0,35	Simulation	MM5	Sailor et al. (2002)
73	Atlanta, USA	0,25–0,35	30	2,5		Simulation	WRF	Zhou et al. (2010)
74	Huston, USA	0,1–0,2	30	3,5	0,4	Simulation	MM5	Taha (2008a)
75	New York, USA	0,3–0,4	28	2	1,1	Simulation	MM5	Lynn et al. (2009)

acteristics of the buried pipes, the speed and mass of the circulated air and more importantly, on the temperature difference between the soil and the ambient air (Mihalakakou et al., 1994a). Although many accurate numerical models are available to calculate the thermal performance of earth to air heat exchangers, the system is not considered by most of the available computational tools used for calculating the microclimate conditions and the impact of the various mitigation techniques (Mihalakakou et al., 1994b).

Earth to air heat exchangers for outdoor cooling were used on a large scale in Seville's Expo 92 (Velazquez et al., 1992). Although detailed monitoring has taken place, data on the specific performance of the system are not available. Recently, several urban mitigation projects considered the use of earth to air heat exchangers as part of their designed mitigation strategy (Fintikakis et al., 2011; Santamouris et al., 2012b). The mitigation potential of the specific projects is reported in the following chapter, where the results of case studies combining more than one mitigation technology are analysed. Some of these projects are built and experimental data regarding the performance of the earth to air heat exchangers is available. Fig. 8 presents the measured inlet and outlet air temperatures in an earth to air heat exchanger installed in a real scale urban rehabilitation project in Athens (Santamouris, 2014b). As

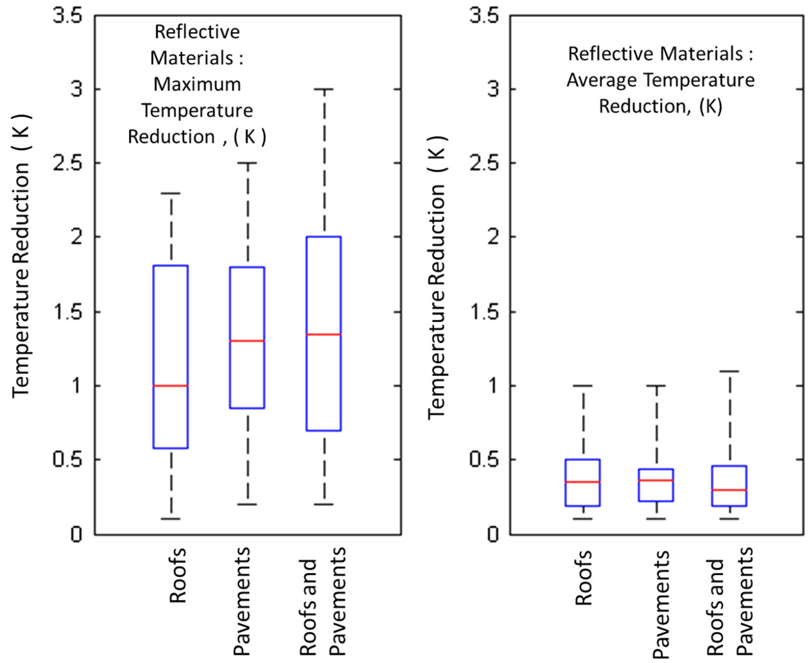

Fig. 4. Range of the average and peak temperature reduction for the different reflective technologies.

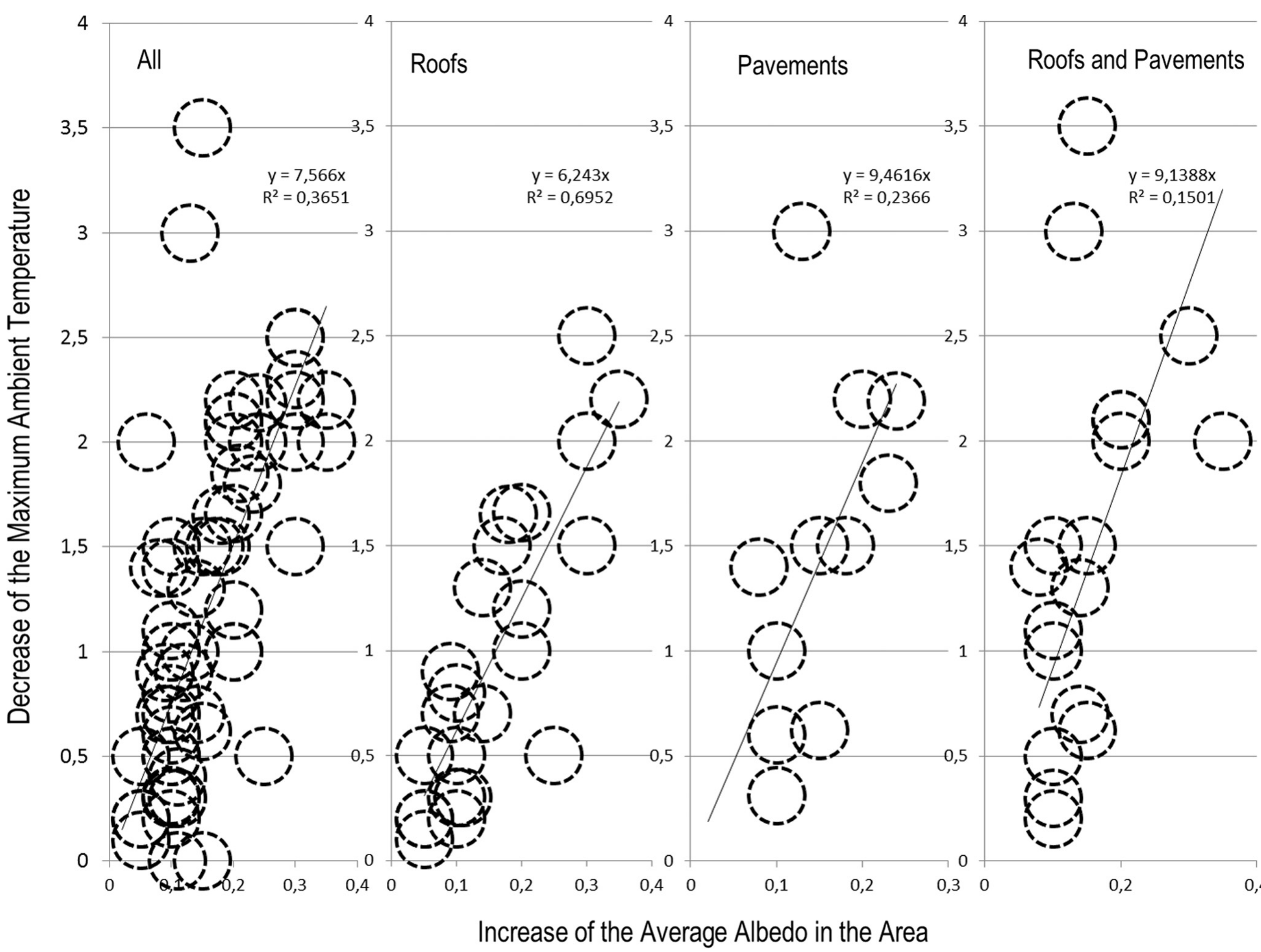

Fig. 5. Decrease of the peak ambient temperature of the various reflective technologies as a function of the albedo increase.

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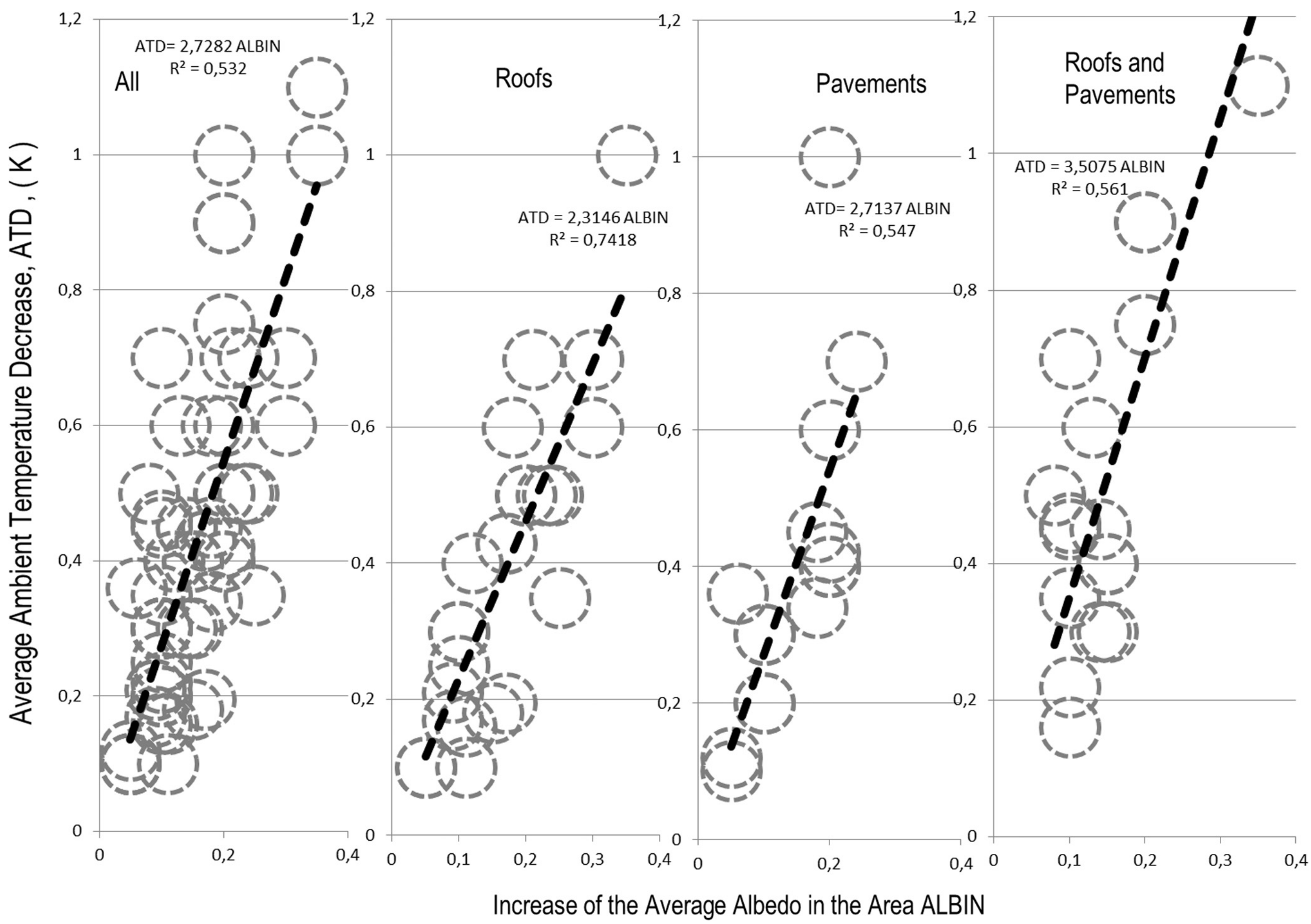

Fig. 6. Decrease of the average ambient temperature of the various reflective technologies as a function of the albedo increase.

shown, during the daytime the temperature drop of the air circulated inside the exchangers may exceed 10 K.

The exact mitigation potential of the ground cooling systems depends mainly on the characteristics and the total number of the installed exchangers, and the climatic characteristics on the considered urban zone. Unfortunately, detailed parametric studies on the mitigation potential of ground cooling are not available like for the other mitigation technologies. Performance data can only be extracted through the analysis of the experimental and theoretical information provided by urban mitigation studies involving the use of ground cooling systems. More analysis on this issue is provided in the following chapter.

6. Combined mitigation strategies

Several technologies and systems may be combined to mitigate the urban heat island. It is of great interest to understand how mitigation technologies of different natures and characteristics may work together and to assess their combined climatic performance. It is important to point out that the final mitigation potential of any combination of mitigation technologies should be quite lower than the sum of the contributions of each individual technology involved. Most of the considered mitigation technologies perform under the same outdoor temperature levels and their thermal interaction reduces the utilisability function of each one individually. Although knowledge of the final performance of a combination of technologies may not provide information on the specific contribution of each one, a comparative statistical analysis between projects may help to better understand their individual contribution. In the following section, 55 urban projects involving a combination of reflective materials, urban greenery, water systems, earth to air heat exchangers and solar control systems, are analysed and conclusions are drawn.

7. Combined use of reflective pavements, greenery, shading and water

The combined use of greenery and reflective materials to improve the microclimate of urban areas is a very popular mitigation strategy. Various combinations among the different greenery systems and the reflective technologies analysed before, are already tested. Twenty-five different projects involving the combined use of urban greenery and reflective materials, are identified and analysed. Details of the considered projects as well as the published performance data are given in Table 4. All performance data result from simulation studies. The range of the peak and average temperature drop for all the projects is given in Fig. 9. The calculated decrease of the peak temperature ranges between 0.4 K and 5 K with a median value close to 1.95 K, while the corresponding drop of the average temperature ranges between 0.1 K and 1.4 K with a median value around to 0.7 K.

Compared to the corresponding performance of the projects involving solely reflective materials, the combined use of greenery and reflective materials increases the peak temperature drop by 0.95 K, while the corresponding rise of the average temperature drop is 0.3 K. It is evident that the use of urban greenery systems

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Table 4
Characteristics and reported performance of projects involving reflective materials and urban greenery technologies.

No	Location	Increase of the albedo in the study area (0–1)	Design temperature (C)	Maximum temperature reduction (C)	Average temperature reduction (C)	Experimental/ simulation	Simulation tool used	Reference
Reflective materials and greenery								
1	Grenoble, France	0,05–0,15	34	0,4	0,2	Simulation	Envi-Met	Pisello et al. (2016)
2	Athens Suburb, Greece	0,15–0,25	37,2	2,1	1,0	Simulation	CFD	GRBES (2016)
3	Phoenix, USA	0,15–0,25	36		0,1	Simulation	WRF	Stone et al. (2014)
4	Athens, Suburb, Greece	0,1–0,2	33	1,5	0,6	Simulation	CFD	GRBES (2016)
5	Atlanta, USA	0,15–0,25	32		0,3	Simulation	WRF	Stone et al. (2014)
6	Athens, Suburb, Greece	0,05–0,15	26	0,5	0,2	Simulation	CFD	GRBES (2016)
7	Athens, Suburb, Greece	0,15–0,25	32	1,8	0,9	Simulation	CFD	GRBES (2016)
8	Toronto, Canada, Greece	0,05–0,15	33	1	0,3	Simulation	Envi-Met	Wang et al. (2016)
9	Flisvos, Athens, Greece	0,20–0,25	32	2,2	0,9	Simulation	CFD	Santamouris et al. (2012b)
10	Ho Chi Minh City, Vietnam	0,03–0,07	28	0,6	0,15	Simulation	Envi-Met	Huynh and Eckert (2012)
11	Central Athens, Greece	0,15–0,25	32	1,5	0,6	Simulation	CFD	Gaitani et al. (2011)
12	Agios Demetrios, Athens, Greece	0,15–0,20	34	1,5	0,55	Simulation	CFD	GRBES (2016)
13	Philadelphia, USA	0,15–0,25	30		0,3	Simulation	WRF	Stone et al. (2014)
14	Mentoza, Argentina	0,10–0,20	36	3,5	1,0	Simulation	Envi-Met	Alchapar et al. (2016)
15	Katerini, Greece	0,3–0,4	32	3	1,4	Simulation	CFD	GRBES (2016)
16	Campinas, Brazil	0,10–0,20	33	5	1,4	Simulation	Envi-Met	Alchapar et al. (2016)
17	Rethimnon, Greece	0,15–0,25	31	1,7	0,7	Simulation	Envi-Met	Tsitoura et al. (2016)
18	Veneto, Italy	0,15–0,25	34	3	0,9	Simulation	Envi-Met	Campostrini (2013)
19	Athinas Avenue, Athens, Greece	0,3–0,4	31	3	1,4	Simulation	CFD	GRBES (2016)
20	Los Angeles, USA	0,15–0,25	33	3,6	1	Simulation	MM5	Taha (2008b)
21	Salonica, Greece	0,10–0,15	40,9	0,9	0,25	Simulation	Envi-Met	Chatzidimitriou et al. (2013)
22	Pomona, USA	0,15–0,25	34	3,4	0,9	Simulation	MM5	Taha (2008b)
23	Katerini, Greece	0,25–0,35	33	3	1,4	Simulation	CFD	GRBES (2016)
24	San Fernando, USA	0,15–0,25	34	3,4	1	Simulation	MM5	Taha (2008b)
25	Dafni, Athens	0,10–0,20	36	1,1	0,4	Simulation	CFD	GRBES (2016)
Reflective materials +greenery and shading								
1	Olympic Village, Athens, Greece	0,20–0,25	39	3,5	1,3	Simulation	CFD	GRBES (2016)
2	Kesariani Square, Athens, Greece	0,15–0,20	35	1,9	0,8	Simulation	CFD	GRBES (2016)
3	North Athens, Greece	0,15–0,20	33	1,8	0,7	Simulation	CFD	GRBES (2016)
4	University Campus, Athens, 2009	0,20–0,25	32	2,3	1,0	Simulation	CFD	GRBES (2016)
5	Athinas Avenue, Athens, Greece	0,3–0,4	31	4	1,9	Simulation	CFD	GRBES (2016)
Reflective materials + greenery + shading + water								
1	Salonica, Greece	0,10–0,15	40,9	2,4	1,1	Simulation	Envi-Met	Chatzidimitriou et al. (2013)
2	Panepistimiou Avenue, Athens	0,10–0,15	33	1,4	0,6	Simulation	Envi-Met	Onassis Foundation (2014)
3	Eastern Macedonia, Greece	0,25–0,35	36	4,4	2,1	Simulation	Envi-Met	Papadopoulos (2016)
4	Suburb Salonica, Greece	0,30–0,40	34	5,8	2,4	Simulation	Envi-Met	Papadopoulos (2016)
Reflective materials + greenery + water								
1	Ptolemaida, Greece	0,15–0,25	32	2,7	1,3	Simulation	CFD	Zoras et al. (2015)
2	Salonica, Greece	0,10–0,15	40,9	2,3	0,9	Simulation	Envi-Met	Chatzidimitriou et al. (2013)
3	Agia Varvara, Athens, Greece	0,20–0,25	36	3,1	1,2	Simulation	CFD	GRBES (2016)
4	Immitos, Athens, Greece	0,05–0,15	33	1,4	0,8	Simulation	Envi-Met	Londorfos et al. (2016)

in addition to the increase of the urban albedo, offers an added mitigation potential for the projects. The resulting peak temperature drop per 10% increase of the albedo is higher by 0.4 K when greenery and cool materials are used in combination, than when just reflective materials are used. In a similar way, the average temperature drop increases by 0.17 K per 10% albedo increase, Figs. 10 and 11.

Reflective materials and greenery may combine with water based and solar control mitigation techniques to further decrease the peak ambient temperature. Four urban rehabilitation projects involving a combined used of reflective pavements, greenery and water for evaporation are reported in Table 4. The calculated drop of the peak and the average ambient temperature is between 1.4–3.1 K and 0.8–1.3 K respectively. The calculated peak temperature drop per 10% of the albedo value is 1.44 K, about 0.3 K higher than the corresponding value for the combination of reflective materials and greenery (Fig. 12). This additional reduction is the added mitigation value offered by the water based systems, however the amount of data is not enough to draw accurate conclusions.

Data from five urban rehabilitation projects involving the combined use of reflective pavements, greenery and shading devices are reported in Table 4. The peak and average temperature drop are calculated between 1.8–4 K and 0.7–1.9 K respectively. The decrease of the peak temperature per 10% increase in the albedo

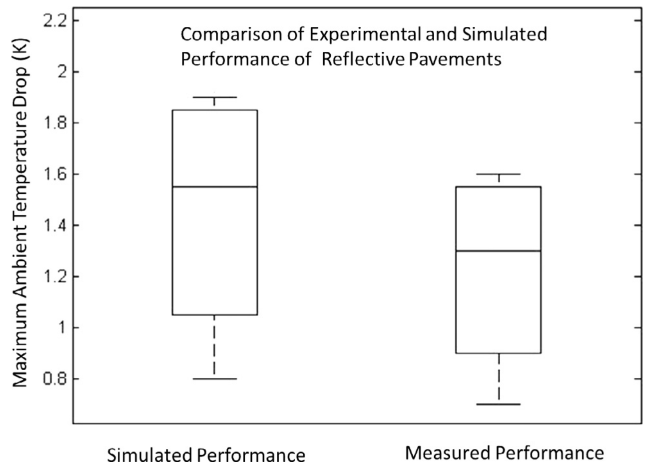

Fig. 7. Comparison of the predicted and experimental temperature drop for four projects using cool pavements.

value is calculated close to 1.29 K, almost 0.16 K more than when solely reflective materials and greenery is used, (Fig. 12). This specific increase of the temperature drop may be attributed to the impact of urban shading devices, (Paolini et al., 2014).

Four projects involving the combined use of reflective pavements, greenery, shading and water are analysed and their characteristics are given in Table 4. The peak and average temperature drop are found to vary between 1.4–5.8 K and 0.6–2.4 K respectively. The peak temperature drop per 10% increase of the albedo is calculated close to 1.51 K, about 0.22 K higher than in the previous case. The specific increase it may attributed to the additional use of water. It is pointed out that the corresponding contribution of water systems as calculated previously was close to 0.3 K.

Two additional projects, one combining greenery, water and solar control and a second one based on the use of greenery and water are also analysed. The reported peak temperature drop is close to 3.5 K and 2.2 K respectively.

8. Projects involving the use of earth to air heat exchangers

Reflective materials to decrease the absorbed solar radiation and the corresponding surface temperature of the materials combined with earth to air heat exchangers to dissipate the excess urban heat into the ground, seems to be a very interesting mitigation combination. Nine projects involving a combined use of reflective pavements and earth to air heat exchangers have been analysed and their characteristics as well as the simulated performance are given in Table 5. The number of the exchangers varies between 3 and 74 while the estimated delivered cooling energy from the exchangers ranges between 0.6 and 10.2 W/m^2 of project area. The maximum drop of the ambient temperature varies between 1.7 K and 2.3 K with a median value close to 1.95 K, while the average temperature drop varies between 0.65 K and 0.9 K with a median value around 0.7 K. Three of the projects are under monitoring (Projects 1, 4 and 5 of Table 5) and preliminary results show a good agreement between the simulated and the experimental results.

To estimate the potential contribution of the earth to air heat exchangers, the peak temperature drops for all projects have been plotted against the corresponding increase of the albedo (Fig. 13). It is found that the peak and average temperature reduction per 10% increase of the albedo are 0.99 K and 0.37 K correspondingly. As previously calculated, the peak and average temperature drop when solely cool pavements are used, is 0.94 K and 0.27 K. Thus, it may be concluded that when earth to air heat exchangers are used in combination with reflective pavements, their average mitigation potential may vary between 0.04 and 0.1 K per 10% increase of the albedo. This is a quite rational estimation given that the cooling contribution of the earth to air heat exchangers in the specific projects did not exceed 10 W/m^2 of the project area. It has to be pointed out that the reduction of the sensible heat caused by the reflective pavements is larger by several tens of times.

Reflective pavements, earth to air heat exchangers and solar control techniques have been employed by four urban mitigation projects. The characteristics of the projects are given in Table 5. The projects employ 3–6 heat exchangers with a flow rate between

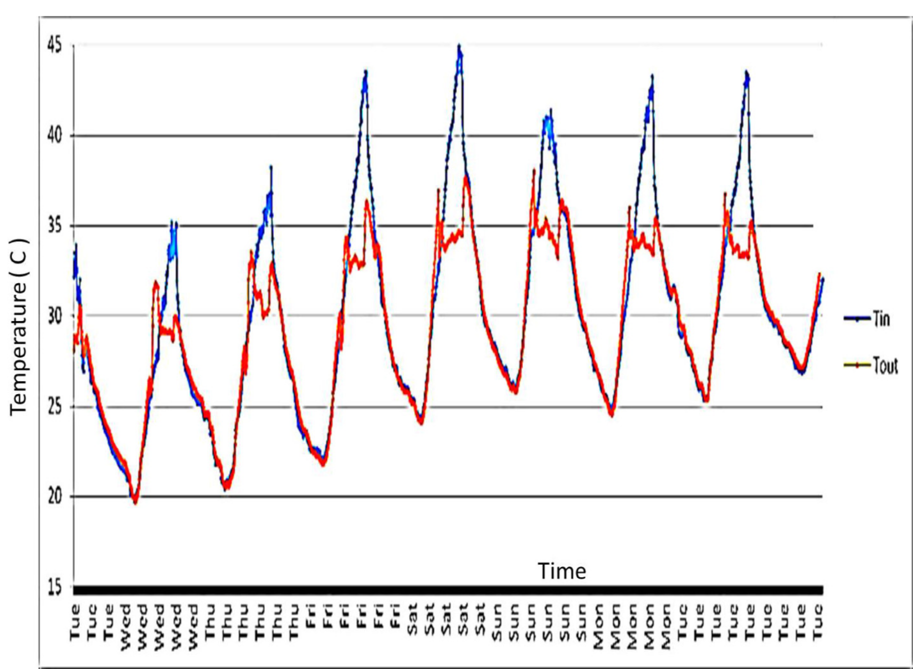

Fig. 8. Inlet and outlet air temperature from an earth to air heat exchanger installed to decrease the ambient temperature in the outdoor environment.

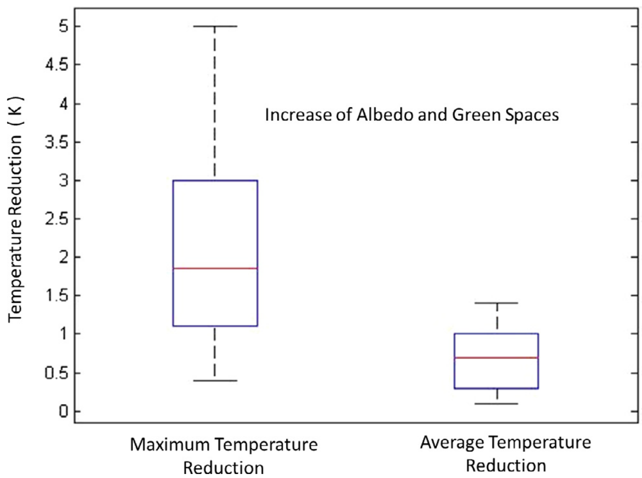

Fig. 9. Range of the maximum and average temperature drop in projects involving reflective materials and greenery technologies.

1100 and 1400 m^3/h. The calculated drop of the maximum ambient temperature varies between 0.14 K and 1.7 K while the corresponding decrease of the average temperature drop is between 0.4 K and 0.7 K. The calculated temperature drop per 10% increase of albedo is close to 1.22 K, about 0,23 K higher than when reflective materials and EAHE are used (Fig. 13). The additional temperature decrease may be attributed to the shading systems, however the number of projects is quite low and accurate conclusions cannot be drawn.

Earth to air heat exchangers combined with reflective pavements, shading and urban greenery is used also by four other urban rehabilitation projects described in Table 5. The number of earth to air heat exchangers were between 4 and 15. The maximum temperature drop varies between 1.7 K and 2.7 K, C while the corresponding decrease of the average temperature is between 0.7 and 1.1 K. The maximum temperature drop per 10% of albedo increase is calculated close to 1.36 K, (Fig. 13), about 0.12 K higher than when earth to air heat exchangers are combined with reflective materials and shading. The additional temperature drop may be attributed to the impact of urban greenery, however, as in the previous case, the number of considered projects is not enough to extract concrete conclusions.

9. Concluding remarks

Urban Heat Island and local climate change effects increase considerably the ambient temperature in cities. Higher urban temperatures have a very significant impact on energy consumption, health, comfort and the environmental quality of cities. Traditional and advanced urban mitigation technologies developed in recent years are proposed and used to counterbalance the impact of local climate change. Proposed technologies involve among others, the use of reflective materials, additional greenery, use of water for evaporation, solar control techniques and earth to air heat exchangers for dissipation of the excess heat to the ground. A quite high number of urban rehabilitation projects have been designed and implemented during the recent years all around the world. The previous analysis of the characteristics and the performance results from almost 220 urban mitigation projects combining several mitigation technologies under various climatic conditions, permits to extract some significant conclusions:

(a) The mitigation potential of the considered technologies is quite high and can counterbalance partly or fully the impact of local climate change and urban heat island. 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, (0–2 K), 82% below 3 K, (0–3 K), and 90% below 4 K.

(b) There is a considerable increase of the mitigation potential when more technologies are combined. The average peak temperature reduction of all projects involving just one technology is close to 1.89 K, and increases up to 2.26 K when two or more technologies are used together. In parallel, only 10% of the projects with more than one mitigation technology, present a peak temperature reduction below 1 K, against 45% of the projects involving just one mitigation technology. The corresponding figures for a 2 K peak temperature reduction are 50% and 73%.

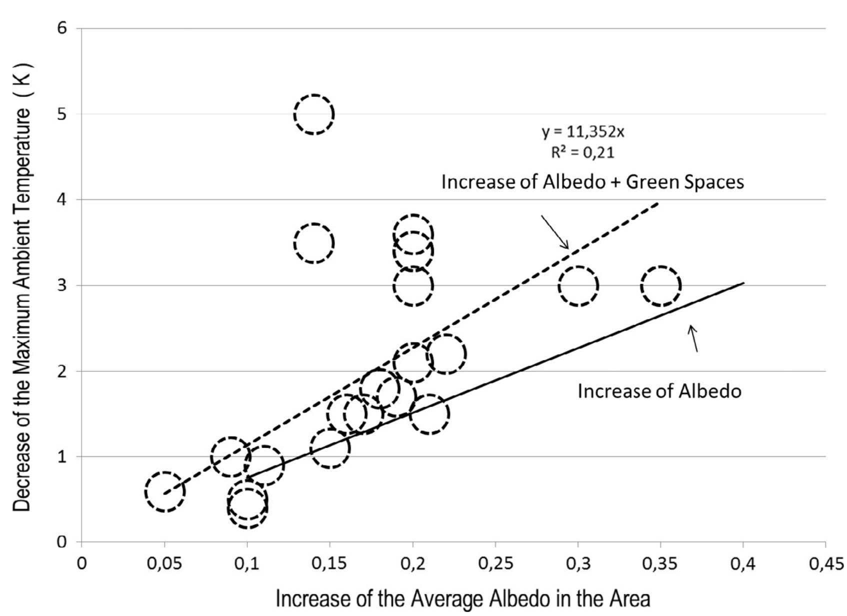

Fig. 10. Decrease of the maximum ambient temperature as a function of the albedo increase for projects involving reflective materials and greenery.

Please cite this article in press as: Santamouris, M., et al. 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. Sol. Energy (2016), http://dx.doi.org/10.1016/j.solener.2016.12.006

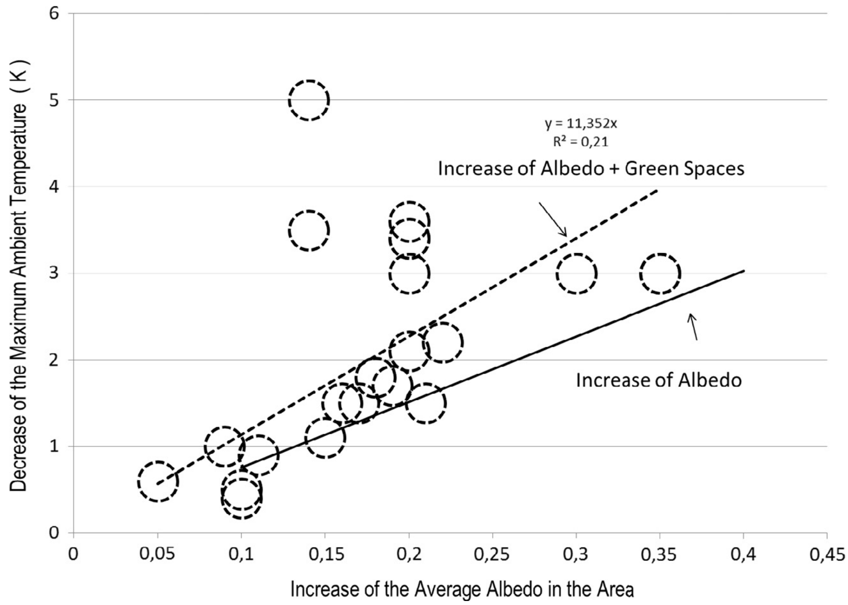

Fig. 11. Decrease of the average ambient temperature as a function of the albedo increase for projects involving reflective materials and greenery.

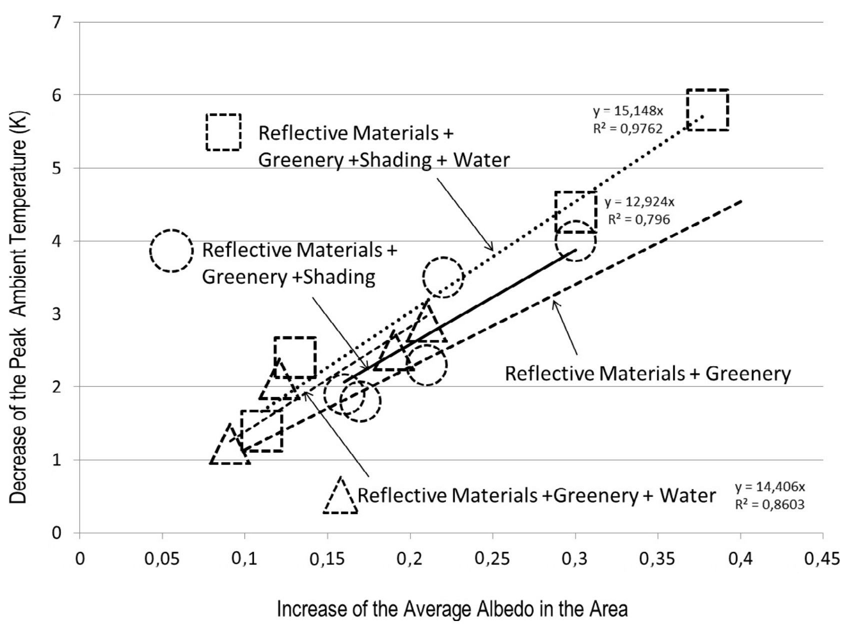

Fig. 12. Decrease of the peak ambient temperature as a function of the albedo increase for projects involving a combination of reflective materials, greenery, water and shading.

(c) There are important differences between the various technologies and their combination as it concerns their mitigation potential. The variability of all technologies and combinations resulting from the analysis of the projects is given in Fig. 14.

(d) Urban greenery is the most popular mitigation technology. Trees and hedges, green roofs, grass and combinations of them are widely used to counterbalance the urban heat island phenomenon. The average peak temperature drop of all greenery projects is close to 1.66 K. About 50% of the greenery projects have a peak temperature reduction below 1 K, 78% below 2 K, (0–2 K), and almost 90% below 3 K, (0–3 K). Urban trees seem to present the highest mitigation potential followed by grass and green roofs. The mitigation potential of the green roofs is found to reduce seriously as a function of the building's height. Almost a negligible mitigation impact is calculated for green roof systems installed in high rise buildings.

(e) The use of reflective materials installed on the roof of buildings or in pavements present a significant mitigation potential. The average peak temperature drop for all projects is close to 1.3 K. About 45% of the projects presented a peak temperature reduction below 1 K and 81% below 2 K, (0–2 K). Reflective pavements seem to present a higher mitigation potential than cool roofs, mainly because of the proximity to the ground level. An almost linear relation is found between the increase of the albedo and the corresponding peak and average temperature drop. It is found that the peak

Table 5
Characteristics and reported performance of projects involving the use of earth to air heat exchangers in combination with other mitigation technologies.

No	Location	Increase of the albedo in the study area (0–1)	Design temperature (C)	Number of heat exchangers	Average flow rate (m^3/h)	Peak temperature drop (C)	Average temperature drop (C)	Reference
Use of reflective materials in combination with EAHE								
1	Marousi, Athens	0,05–0,15	36	3	1450	1,05	0,35	Santamouris et al. (2012b)
2	Western Greece	0,15–25	32,5	54	565	1,9	0,7	Kolokotsa (2011)
3	Western Athens, Greece	0,20–0,30	39	20	565	2,3	0,9	Kolokotsa (2011)
4	Western Athens2, Greece	0,15–0,25	39	20	565	1,95	0,8	Kolokotsa (2011)
5	Thessaly, Greece	0,15–0,20	40	40	600	1,7	0,85	Kolokotsa (2011)
6	South Peloponese, Greece	0,15–0,20	33	74	600	1,85	0,65	Kolokotsa (2011)
7	Central Greece	0,15–0,25	33	4	1100	2,15	0,6	GRBES (2016)
8	Northern Athens, Greece	0,2–0,25	37	12	565	2,15	0,8	Kolokotsa (2011)
9	Ioanian Island, Greece	0,2–0,30	39	4	565	2	0,65	Kolokotsa (2011)
Reflective materials in combination with EAHE and shading								
1	Central Athens, Greece	0,15–0,25	32	6	1420	1,7	0,7	Gaitani et al. (2011)
2	Central Athens, Greece	0,10–0,15	32	3	1230	1,6	0,6	GRBES (2016)
3	South Athens, Greece	0,10–0,15	32	4	1150	1,6	0,45	GRBES (2016)
4	Northern Athens	0,05–0,15	33	5	1200	1,4	0,4	Gaitani et al. (2014)
Reflective materials in combination with EAHE, shading and greenery								
1	Central Western Athens, Greece	0,10–0,15	35	6	1150	1,8	0,8	GRBES (2016)
2	Central Northern Athens	0,15–0,20	33	4	1200	2,7	1,1	GRBES (2016)
3	Western Athens	0,10–0,20	33	4	1300	1,7	0,75	GRBES (2016)
4	Tirana, Albania	0,15–0,20	33	15	1800	2,1	1	Fintikakis et al. (2011)

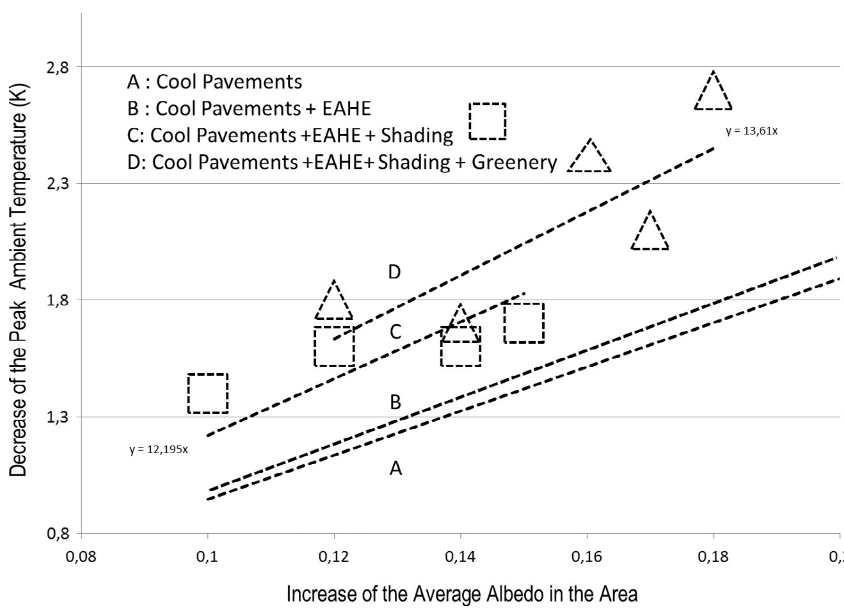

Fig. 13. Decrease of the peak ambient temperature as a function of the albedo increase for projects involving a combination of earth to air heat exchangers and of other mitigation techniques.

temperature is reduced by 0.78 K per 10% increase of the urban albedo. Ageing seems to be an important problem for projects involving reflective materials. The experimentally assessed mitigation potential of four projects applying cool pavements is found to be 16% lower than the simulated performance

(f) Water is widely used as a heat sink to mitigate urban heat island. Water based technologies involve the use of conventional systems like pools, ponds and fountains, but also of more advanced technologies like micronizers, sprinklers and evaporative towers. The average peak temperature drop calculated for the 17 water base projects is close to 4.5 K and is mainly due to the high temperature drop associated with the use of sprinklers and evaporative towers. About 28% of the projects present a peak temperature drop lower than 2 K, (0–2 K), 45% below 4 K, (0–4 K), and 65% below 6 K, (0–6 K). It has to be pointed out that most of the data are collected from dry climatic zones enhancing the use of evaporative cooling, and in a short distance from the water systems. Water based techniques may present a reduced mitigation potential when used in humid climates. In parallel, sprinklers and evaporative coolers are excellent solutions for small to medium size dry areas, but have a quite local impact and cannot cover very large areas like reflective materials and urban greenery do.

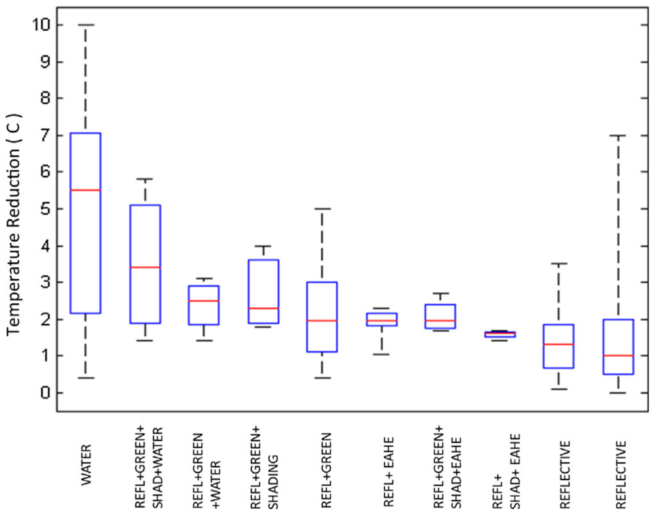

Fig. 14. Range of the peak ambient temperature reduction for all the considered mitigation systems and technologies.

Table 6
Calculated decrease of the peak ambient temperature of the various mitigation technologies as a function of the albedo increase.

Mitigation technology	Decrease of peak temperature per 10% increase of albedo (K)
Cool roofs	0,60
All reflective technologies	0,70
Cool pavements	0,95
Cool pavements and earth to air heat exchangers	1,00
All reflective technologies and greenery	1,10
Reflective pavements and EAHE and shading	1,20
Reflective pavements and greenery and shading	1,30
Reflective pavements and greenery and shading and EAHE	1,40
Reflective pavements and greenery and water	1,45
Reflective pavements, shading, greenery and water	1,50

(g) When reflective materials are combined with other mitigation technologies the resulting drop of the peak ambient temperature increases considerably. In this case, the slope of the curve between the albedo increase and the temperature drop is rising because of the climatic contribution of the combined mitigation technologies. Table 6 reports the calculated equivalent peak temperature drop per 10% increase of the albedo. As shown, while reflective materials may contribute to a temperature reduction between 0.6 and 0.95 K per 10% increase of the albedo, the equivalent contribution of the combined technologies may increase up to 1.5 K.

(h) Comparison of the slope of the curves between the peak temperature decrease and the albedo for all the combination of technologies, could provide a rough estimation of the additional mitigation contribution of the systems combined with reflective technologies. It has been found that the additional contribution of urban greenery and shading technologies is close to 0.2 K, while the corresponding contribution of water and EAHE technologies are between 0.3–0.4 K and 0.05–0.1 K respectively. In a general way, the greater the number of combined technologies the less the absolute contribution of each of them.

Mitigation technologies can highly counterbalance the impact of local climate change and urban heat island. Existing mitigation technologies applied at the city or neighbourhood scale may reduce the peak ambient temperature up 2–3 K. A further decrease may be achieved in smaller urban zones using advanced evaporation technologies, provided that the local climate is dry.

There is a need to develop more efficient mitigation technologies able to further decrease the ambient temperature and counterbalance the local climate change. This goal may be achieved either by developing materials able to present and keep their surface temperatures below the ambient or by large scale dissipation of the excess urban heat to a low temperature heat sink, or through technologies combining both principles.

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Please cite this article in press as: Santamouris, M., et al. 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. Sol. Energy (2016), http://dx.doi.org/10.1016/j.solener.2016.12.006