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Cooling the cities – A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments

M. Santamouris

Group Building Environmental Research, Physics Department, University of Athens, Athens, Greece

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Abstract

The temperature of cities continues to increase because of the heat island phenomenon and the undeniable climatic change. The observed high ambient temperatures intensify the energy problem of cities, deteriorates comfort conditions, put in danger the vulnerable population and amplify the pollution problems. To counterbalance the phenomenon, important mitigation technologies have been developed and proposed. Among them, technologies aiming to increase the albedo of cities and the use of vegetative – green roofs appear to be very promising, presenting a relatively high heat island mitigation potential. This paper aims to present the state of the art on both the above technologies, when applied in the city scale. Tenths of published studies have been analysed. Most of the available data are based on simulation studies using mesoscale modeling techniques while important data are available from the existing experimental studies. When a global increase of the city's albedo is considered, the expected mean decrease of the average ambient temperature is close to 0.3 K per 0.1 rise of the albedo, while the corresponding average decrease of the peak ambient temperature is close to 0.9 K. When only cool roofs are considered, the analysis of the existing data shows that the expected depression rate of the average urban ambient temperature varies between 0.1 and 0.33 K per 0.1 increase of the roofs albedo with a mean value close to 0.2 K. As it concerns green roofs, existing simulation studies show that when applied on a city scale, they may reduce the average ambient temperature between 0.3 and 3 K. Detailed analysis of many studies reporting a comparison of the mitigation potential of both technologies has permitted the definition of the limits, the boundaries and the conditions under which the considered technologies reach their better performance, in a synthetic way.

Keywords: Heat island; Cool roofs; Green roofs; Mitigation potential

1. Introduction

Heat island is the most documented phenomenon of climate change. The phenomenon is known for almost a century and is related to higher urban temperatures compared to the adjacent suburban and rural areas (Santamouris, 2001). Higher urban temperatures are due to the positive thermal balance of urban areas caused by the important release of anthropogenic heat, the excess storage of solar radiation by the city structures, the lack of green spaces and cool sinks, the non-circulation of air in urban canyons and the reduced ability of the emitted infrared radiation to escape in the atmosphere (Oke et al., 1991).

During the recent period, intensive research has been carried out on the topic, the impact and the significance, as well as the qualitative and quantitative characteristics of the phenomenon are much better documented (Santamouris, 2007; Mirzaei and Haghighat, 2010; Founda, 2011; Stewart, 2011; Mihalakakou et al., 2002; Mihalakakou et al., 2004; Livada et al., 2002; Mohsin and Gough, 2012; Klok et al., in press; Papanastasiou and Kittas,

E-mail address: msantam@phys.uoa.gr

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2012). Higher urban temperatures increase the energy consumption for cooling and raise the peak electricity demand (Hassid et al., 2000; Cartalis et al., 2001; Santamouris et al., 2001; Kolokotroni et al., 2012; Hirano and Fujita, in press; Akbari and Konopacki, 2004; Akbari et al., 1992). As mentioned by Santamouris et al. (2001), heat island in the city of Athens, Greece, doubles the cooling load of buildings and almost triples their peak electricity demand, while decreasing the Coefficient of Performance (COP), of mechanical cooling systems up to 25%. According to Akbari et al. (1992), for US cities with population larger than 100,000 the peak electricity load will increase 1.5–2% for every 1 °F increase in temperature. The cooling energy increase is accompanied by intensification of pollution patterns in cities and increase of ozone concentrations (Stathopoulou et al., 2008; Sarrat et al., 2006; Taha, 2008a), while the ecological footprint of the cities is increased (Santamouris et al., 2007a), the outdoor thermal comfort conditions deteriorate (Pantavou et al., 2011), the thermal stress in low income dwellings is increased, the indoor thermal comfort levels are seriously decreased and health problems are intensified (Sakka et al., 2012; Luber and McGeehin, 2008).

Research carried out recently has permitted the development of technological measures to counterbalance the impact of heat island (Rosenfeld et al., 1995; Akbari et al., 2001; Adnot et al., 2007; Kuttler, 2011; Gaitani et al., 2007). Mitigation techniques aim to balance the thermal budget of cities by increasing thermal losses and decreasing the corresponding gains. Among the more important of the proposed techniques are those targeting to increase the albedo of the urban environment, to expand the green spaces in cities and to use the natural heat sinks in order to dissipate the excess heat (Akbari et al., 2005a; Julia et al., 2009; Mihalakakou et al., 1994). Recent real scale applications involving the use of the above mitigation techniques have resulted into very important climatic benefits and a serious reduction of the heat island strength (Gaitani et al., 2011; Fintikakis et al., 2011; Santamouris et al., in press, 2012).

Roofs present a very high fraction of the exposed urban area. Estimations given in Akbari and Rose (2008), for four American cities, show that the roof area fraction varies from 20% to 25% for less or more dense cities. Based on these findings and considering that urban areas occupy almost 1% of all land, it is estimated that the total roof area of the urban world is close to 3.8×10^{11} m^2 (Akbari et al., 2009a). However, according to Jacobson et al. (2007), the above assumption regarding the size of urban areas is about 2.26 times higher than it is estimated using an analysis of satellite data.

Given that the available free ground area in the urban environment is quite limited and of very high economic value, it is relatively difficult to implement large scale mitigation technologies on the ground surface of cities. At the same time, urbanization decreases the proportion of spaces dedicated to plants and trees or other mitigation infrastructures because of new building developments (Mathieu et al., 2007; Smith, 2010). On the contrary, roofs provide an excellent space to apply mitigation techniques, given that the relevant cost is limited, while the corresponding techniques are associated to important energy savings for the buildings.

Two are the more important mitigation technologies associated to roofs: (a) Those aiming to increase the albedo of the roofs, known as *cool or reflective roofs* (Zinzi, 2010; Akbari and Levinson, 2008; Synnefa and Santamouris, in press) those that propose roofs partially or completed covered with vegetation, known as green roofs or living roofs (Theodosiou, 2009; Santamouris et al., 2007b; Sfakianaki et al., 2009). Both technologies can lower the surface temperatures of roofs and thus to decrease the corresponding sensible heat flux to the atmosphere.

Cool or reflective roofs are typically white and present a high albedo. Products used in cool roofs are single ply or liquid applied (Mac Cracken, 2009). Typical liquid applied products involve white paints, elastomeric, polyurethane or acrylic coatings. Examples of white single ply products involve EPDM (Ethylene-Propylenediene-Tetrolymer Membrane) PVC (Polyvinyl Chloride), CPE (Chlorinated Polyethylene), CPSE (Chlorosulfonated Polyethylene), and TPO (Thermoplastic Polyolefin) materials (Mac Cracken, 2009).

A review of the recent developments on the field of liquid applied materials used in reflective roofs is given in Santamouris et al. (2011). The first generation of materials used in cool roofs consisted of natural materials quite easily found in the nature characterized by a relatively high albedo, rarely higher than 0.75 (Doulos et al., 2004; Bretz et al., 1992; Reagan and Acklam, 1979), while the second generation was based on the development of artificial white materials designed to present very high albedo values close or higher than 0.85 (Synnefa et al., 2006; Kolokotsa et al., 2012; Santamouris et al., 2008). In a later, third phase of development, colored high reflective materials have been developed. The overall idea was to develop colored materials presenting a high reflectivity value in the infrared spectrum (Levinson et al., 2005a, 2005b; Synnefa et al., 2007a). The specific materials were characterized by a much higher global reflectivity than the conventional ones of the same color and were associated to important energy savings when used in building roofs or urban infrastructures (Synnefa et al., 2007b, 2011; Santamouris et al., 2007c). Quite recently, fourth generation reflective materials based on nanotechnological additives like thermochromic paints and tiles (Ma et al., 2001, 2002; Karlessi et al., 2009), or PCM doped cool materials (Karlessi et al., 2011; Zhang et al., 2007; Pasupathy et al., 2008; Cabeza et al., 2007) have been developed and likely to be used for future cool roof applications.

Many studies have been performed in order to identify the cooling potential and the possible improvements of indoor thermal comfort caused by cool roofs (Synnefa et al., in press; Akbari et al., 2005a, 2005b; Levinson et al., 2005c; Tengfang et al., 2012; Kolokotsa et al., in press; Romeo and Zinzi, in press; Kolokotroni et al., in press; Bozonnet et al., 2011; Boixo et al., 2012; Takebayashi et al., in press). Energy benefits vary mainly as a function of the climatic conditions and the characteristics of the building. Typically, peak summer indoor temperatures may decrease up to 2 °C in moderately insulated buildings while cooling loads reductions may range between 10% and 40%. At the same time, the heating penalty may range between 5% and 10% as a function of the local climate and building characteristics.

In parallel, important simulation studies have been carried out to identify the heat island mitigation potential of cool roofs (Savio et al., 2006; Synnefa et al., 2008; Menon et al., 2010; Jacobson and Ten Hoeve, 2012). Low temperatures at the roof level, decrease the sensible heat flux to the atmosphere and add to the mitigation of the urban heat island. Most of the studies have been carried out in USA, using mesoscale simulation models. The specific results of the above studies are discussed in the following chapters.

Increase of the green spaces in cities, contribute to decrease the urban surface and ambient temperatures and mitigate heat island effect. Studies reported by Gill et al. (2007), show that an increase by 10% of the urban green in Manchester, UK, could amortize the predicted increase by 4 K, of the ambient temperature over the next 80 years. Green or living roofs are partially or fully covered by vegetation and a growing medium over a waterproofing membrane. There are two main types of green roofs: Extensive roofs which are light and are covered by a thin layer of vegetation and intensive roofs which are heavier and can support small trees and shrubs. Green roofs present a variety of advantages like storm water runoff management, increased roof materials durability, decreased energy consumption, possible better air quality and noise reduction, offer space for urban wildlife and increased mitigation of urban heat island (Parizotto and Lamberts, 2011; Mentens et al., 2006; Teemusk and Mander, 2009; Rowe, 2010; Renterghem and Botteldooren, 2011; Brenneisen, 2006; Pataki et al., 2011).

Several experimental and theoretical studies have been performed to identify the energy conservation potential of green roofs (Kumar and Kaushik, 2005; Alexandri and Jones, 2007; Wong et al., 2003a; Theodosiou, 2003; Eumorfopoulou and Aravantinos, 1998; Jaffal et al., 2012; Spala et al., 2008; Takakura et al., 2000; Castleton et al., 2010). The specific energy benefits depend on the local climate, the green roof design and more importantly on the specific building characteristics. Given that in green roofs heat transfer benefits are mainly provided through latent heat processes, the performance of the system is higher in dry climates. In parallel, the thickness and the thermal characteristics of the vegetative roof largely define its U value and the corresponding transfer of heat to the building, while the type and characteristics of the plants (LAI), define the shading levels and the transfer of radiation through the layers. Finally, watering is important as it determines the latent heat release and regulates the thermal balance of the roof. However, the building characteristics also define the possible contribution of green roofs. In non-insulated buildings the impact of green roofs is much higher than in insulated ones. It is evident that the better the insulation of the roof, the lower the contribution of the green roof. In parallel, the characteristics of the energy load of the building define the specific contribution of the roof system. In buildings presenting a high part of their energy load because of the ventilation gains or losses, internal or solar gains, green roofs have a limited contribution. On the contrary, in buildings where the energy load is due to the heat transfer though the opaque parts of the envelope, vegetative roofs may contribute significantly to reduce heating and cooling loads. Existing studies performed for various types of buildings, green roof characteristics and climatic zones, show that expected reduction of the annual energy load may vary between 1% and 40% in extreme cases. In reality, in well insulated modern buildings the energy contribution of green roofs is quite modest.

Although the possible energy contribution of green and reflective roofs is a quite well investigated area, the available information on the possible mitigation potential of both technologies is relatively limited (Cameron et al., 2012). Most of the existing studies are based on mesoscale simulation modeling and the given results depend completely on the specific regional characteristics and the assumptions made, while very few experimental studies are available. Some of the reported studies attempt to compare the climatic potential of the two roof technologies either using simulation or experimental techniques. However, most of the studies are building and climatic specific and it is quite difficult to extract general conclusions, although the provided results are very useful.

The objective of the present paper is to review, in a critical way, the available scientific information on the mitigation potential of reflective and green roofs. Also, to combine and analyze the existing theoretical and experimental data, compare and homogenize the results and if possible, to provide general conclusions and suggestions.

2. Increasing the albedo in the city: the role of cool roofs

It is well known and documented that large scale change of albedo has a serious impact on the local peak ambient temperature. Multiyear observations reported in Campra et al. (2008), show an important temperature reduction (−0.3 K/decade), because of the massive construction of high albedo greenhouses through the Almeria area in Spain. Several simulation studies have been carried out to investigate the impact of various albedo related mitigation techniques on the possible reduction of ambient temperature. Most of the works evaluate the impact of a general increase of the local albedo considering in a combined way cool roofs, cool pavements roadways and parking lots, while few studies consider and evaluate just the mitigation impact of reflective roofs. In parallel, many of the mitigation studies investigate the combined impact of several and different mitigation technologies, i.e. increase of the local albedo and vegetative cover without splitting the results about the specific contribution of each technique (Taha et al., 1999). The present paper considers only studies aiming either to calculate the influence of reflective roofs or to evaluate the combined impact of a general albedo change.

2.1. Mitigation potential of cool roofs

Evaluation of the heat island mitigation potential of cool roofs in a city is a quite new scientific subject. Four specific studies are currently available focusing on the potential decrease of the ambient temperature because of the increase of roof albedo (Savio et al., 2006; Synnefa et al., 2008; Menon et al., 2010; Jacobson and Ten Hoeve, 2012). Two of the studies (Savio et al., 2006; Synnefa et al., 2008), examine the local impact of cool roofs in New York, US and Athens Greece, while the studies reported by Menon et al. (2010) and Jacobson and Ten Hoeve (2012), investigate the climatic impact of reflective roof on a planetary scale.

In Savio et al. (2006), the impact of cool roofs on the potential ambient temperature decrease at 2 m height above ground, has been evaluated for New York city, US, using simulations performed with the Penn State/NCAR MM5 regional climate model (Grell et al., 1994). Runs were performed for the period of three heat waves during the summer of 2002. An average solar reflectivity equal to 0.5 was used. It was calculated that the daily average temperature decrease in the various parts of the city ranges between 0.18 K and 0.36 K. In parallel, the average 3PM reduction of peak ambient temperature ranged between 0.31 K and 0.62 K as a function of the characteristics of the considered areas.

The climatic impact of cool roofs has been simulated for the city of Athens, Greece (Synnefa et al., 2008). The study has been performed using the MM5 climate model (Grell et al., 1994), for the 15th of August 2005. Two modified albedo scenarios were considered: a moderate one, where the albedo of the roofs was increased from 0.18 to 0.63, and an extreme one where the final albedo of the building rooftops was considered 0.85. It was calculated that for the moderate increase of the albedo, the ambient temperature depression at 2 m height at 12:00 LST varied between 0.5 and 1.5 K. For the extreme case of albedo increase, the ambient temperature reduction varied between 1 K and 2.2 K. The temperature depression found to start at 9:00 LST and stopped at around 20:00 LST.

Simulations were carried out using the CSCRC model (Yoshida et al., 2000; Hong et al., 2004), to calculate the impact of cool roofs in medium and high rise neighborhoods with medium and high rise buildings (average height 28.6 and 67.4 m respectively). The albedo of the roofs was changed from 0.2 to 0.5. It was calculated that the decrease of the ambient temperature at street level was 0.1 K and 0.12 K for the areas of high and medium height rise buildings. It is evident that the impact of reflective roofs on the ambient temperature at street level is seriously reduced when the height of buildings where cool roofs are applied is great.

The characteristics of the NY and Athens studies are summarized in Table 1. The expected rate of temperature depression per 0.1 increase of the albedo of roofs ranges between 0.1 and 0.19 K for New York and 0.11–0.33 K for Athens. The average temperature depression for both studies is close to 0.2 K per 0.1 increase of roof albedo, while the corresponding minimum and maximum temperature depression are 0.02 K and 0.41 K, respectively.

Simulations have been carried out using the GATOR–GCMOM model (Jacobson et al., 2007), to calculate the climatic impact of cool roofs on a planetary scale. The solar albedo of all roofs was increased from 0.12 to 0.65. This corresponds to an overall urban albedo increase by 0.147. It is reported that a worldwide conversion to cool roofs will contribute to decrease populated weighted temperatures by 0.02 K but to increase the overall earth temperature by 0.07 K. The results of this study suggesting an overall global warming because of the possible conversion of roofs to white have been discussed in Oleson et al. (2008a,b), raising several concerns about the assumptions and the results of this publication.

Another similar simulation study aiming to evaluate the worldwide heat island mitigation potential of reflective roofs is reported in Menon et al. (2010). The study was carried out using the urban canyon model CLMU coupled with other models (Oleson et al., 2008a,b). It was considered that the albedo of roofs increases up to 0.9. It is calculated that the daily maximum urban temperatures decrease by 0.6 K while the daily minimum ambient temperature decreased by 0.3 K. This corresponds to a decrease in the urban diurnal temperature range of 0.3 K.

2.2. Increasing the albedo of cities – mitigation potential

One of the first evaluations of the climatic impact of reflective surfaces was published in Sailor (1995). The authors simulated the impact of albedo modification in Los Angeles, USA. They have used the Colorado State University Mesoscale Model (Mahrer and Pielke, 1977). It was assumed that the albedo of downtown surfaces was increased by 0.14 while the corresponding increase for the entire basin was close to 0.08. It was calculated that the considered albedo change reduced ambient temperatures by at least 0.5 K over the majority of the area, while the peak urban temperatures reduction was 1.4 K near downtown LA.

A second study carried out for the same city, Los Angeles, USA, is described in Rosenfeld et al. (1995). The Colorado State University Mesoscale Model (Mahrer and Pielke, 1977), was also used. The authors assumed an increase of the average albedo by 0.13, and in particular from 0.13 to 0.26 for an area of 100,000 km^2, in which over 20% of the land was covered by artificial surfaces. Flat and

Table 1
Characteristics of the New York and Athens studies on the mitigation potential of cool roofs.

Reference work	Area of application	Simulation tool	Final albedo	Results – mitigation potential	Peak temperature depression per 0.1 albedo increase
Savio et al. (2006)	New York City US	Penn State/NCAR MM5	0.5	The daily average temperature reduction ranges between 0.18 K and 0.36 K. The average 3PM reduction of peak ambient temperature ranged between 0.31 K and 0.62 K	0.10–0.19 K
Synnefa et al. (2008)	Athens, Greece	MM5	Scenario a: 0.63	Scenario a: The ambient temperature depression at 2 m height at 12:00 LST varied between 0.5 and 1.5 K	Scenario a: 0.11–0.33 K
			Scenario b: 0.85	Scenario b: The ambient temperature decrease varied between 1 K and 2.2 K	Scenario b: 0.15–0.33 K

sloped roofs accounted for about 30% of the area. For the flat roofs it was considered that the albedo changes from 0.25 to 0.75 while for the sloped roofs from 0.25 to 0.6. It was calculated that the peak impact of the albedo change occurs in the early afternoon and the potential cooling exceeds 3 K at 3 pm. Simulations carried out under different boundary conditions indicate that the expected peak summertime temperature reductions were between 2 and 4 K.

In another study of the same group (Rosenfeld et al., 1998), the cooling potential of a possible albedo change in the city of Los Angeles was evaluated. It was considered that in almost 1250 Km^2 of roof surface the albedo was increased by 0.35 and in particular from 0.15 to 0.5. It was also considered that in 1250 km^2 of pavements, the albedo was increased by 0.25, from 0.05 to 0.30. It was calculated that the achieved temperature reduction during the peak period was close to 1.5 K. Important energy and pollution benefits were also estimated.

Research carried out by Millstein and Menon (2011), has investigated the impact of albedo change on the temperature status of various American cities. Millstein and Menon used the Weather Research and Forecasting model (Skamarock et al., 2008). Cool roofs and cool pavement technologies were considered. It was assumed that roofs and pavements represent 25% and 35% of the urban area respectively, while the considered albedo increase for roofs and pavements were +0.25 and +0.15, respectively. The average albedo increase for the whole considered area ranges between 0.0 and 0.115. It was calculated that cool roofs and cool pavements contribute to decrease average afternoon summertime temperatures by 0.11–0.53 K. For some of the studied urban locations not statistically significant temperature reduction was found.

Simulations are carried out using the mesoscale model MM5 (Grell et al., 1994) to estimate the impact of a possible increase of albedo in Philadelphia, US (Sailor et al., 2002). It was reported that an increase of the local albedo by 0.1 is responsible for an average daytime ambient temperature depression of about 0.3–0.5 K.

A simulation study aiming to investigate the impact of various mitigation technologies for the city of Atlanta, US is described in Zhou and Shepherd (2010). The Weather Research and Forecasting WRF-NOAH land surface model was used (Skamarock et al., 2008). Considering an increase of the local albedo by 100% (0.15–0.30), it was calculated that the ambient temperature depression was almost negligible. On the contrary, when the local albedo rises to 0.45, which corresponds to an increase by 200%, the peak ambient temperature in the city decreases by 2.5 K.

Simulations have been carried out to investigate the impact of a moderate increase of local albedo in Houston, US, using the mesoscale model MM5 (Taha, 2008b). Roof albedo increased from 0.1 to 0.3, wall albedo from 0.25 to 0.3 and paved surface albedo from 0.08 to 0.2. It is found that the change of the albedo may decrease peak tempera-

Table 2
Characteristics of the existing studies on the mitigation potential of increased urban albedo.

Reference	City	Simulation tool used	Albedo change (0–1)	Initial/final albedo	Average decrease of ambient temperature (K)	Peak ambient temperature decrease (K)	Decrease of Taver per 0.1 increase of albedo	Decrease of Tmax per 0.1 increase of albedo
Sailor (1995)	Los Angeles, US	Colorado State University Mesoscale Model	0.14	–	$\sim$0.5 K	1.4 K	0.35 K	1.0 K
Rosenfeld et al. (1995)	Los Angeles, US	The Colorado State University Mesoscale Model	Average Albedo:0.13	Average Albedo 0.13/0.26	$\sim$0.8 K	3.0 K	0.61 K	2.3 K
			Albedo of urban surfaces 0.30	Albedo of urban surfaces rises to 0.50.				
Rosenfeld et al. (1998)	Los Angeles, US	The Colorado State University Mesoscale Model	0.35 for roofs	0.15/0.5 for roofs	–	1.5 K	–	0.5 K
			0.25 for pavements	0.05/0.3 for pavements				
Millstein and Menon (2011)	Various US cities	Weather Research and Forecasting model	0.25 for roofs	–	$\sim$0.11–0.53 K	–	0.05–0.26 K	–
			0.15 for pavements (0.0 to +0.115)					
Sailor et al. (2002)	Philadelphia, US	MM5	0.1	–	$\sim$0.3–0.5 K	–	0.3–0.5	–
Zhou and Shepherd (2010)	Atlanta, US	Weather Research and Forecasting WRF-NOAH land surface model	0.15	0.15/0.3	–	Negligible	–	0.0 K
			0.30	0.15/0.45		2.5 K		0.83 K
Taha (2008a)	Huston, US	MM5	0.2 for roofs 0.05 for walls 0.18 for pavements	0.1/0.3 for roofs 0.25/0.3 for walls 0.08/0.2 for pavements	$\sim$0.3–0.4	3.5 K	0.23	2.0 K
Lynn et al. (2009	New York, US	MM5	0.35	0.15/0.5	$\sim$0.3 K	0.5 K	0.09	0.15 K
Taha (2008c)	Various Cities in California, US	PSU/NCAR MM5	Variable	Scenario a: 0.117–0.152/0.18–0.252 Scenario b: 0.117–0.152/0.199–0.374	Scenario 1: 0.4 K Scenario 2: 0.8 K	Scenario a: 1.0 K Scenario b: 2.0 K	Scenario a: 0.4 K Scenario b: 0.55 K	Scenario a: 1.0 K Scenario b: 1.3 K

tures up to 3.5 K, while in one occasion ambient temperatures increase by up to 1.5 K. The average temperature reduction varies from site to site and ranges between 0.3 and 0.4 K in residential urban areas. Cooling occurs during daytime and heating during the night.

A similar simulation study aiming to evaluate the climatic impact of various mitigation techniques is described in Lynn et al. (2009). The study refers to the Metropolitan New York Area, US, and is carried out using mainly the MM5 mesoscale simulation model. As it concerns the evaluation of the scenario related to the increase of the urban albedo, it was considered that the albedo of the impervious surfaces changes from 0.15 to 0.5. It is found that peak ambient temperature at 2 m height for 12:00 LST 14th August 2001, decreases between 0.25 and 0.5 K, while a daily average temperature decrease is close to 0.2–0.3 K.

Simulations studies have been performed to investigate the impact of various mitigation techniques for several cities of California (Taha, 2008c). The study has been carried out using the PSU/NCAR MM5 simulation tool (Dudhia, 1993). Two scenarios related to the albedo change were considered and evaluated. The first scenario considered a moderate increase of the urban reflectivity while the second one a stronger increase. In particular, for the existing situation, albedos ranged from 0.117 to 0.152, for the moderate albedo change scenario from 0.18 to 0.252, while for the last scenario from 0.199 to 0.374. Data were calculated for Los Angeles, Pomona and San Fernando Valley. It was found that a moderate change of the urban albedo may decrease peak ambient temperatures by up to 1 K, while a stronger change of the albedo contributes to decrease peak ambient temperatures up to 2 K.

Details of all the previously presented studies are given in Table 2. Existing studies refer to a possible increase of the urban albedo ranging between 0.01 and 0.35. The calculated decrease of the average ambient temperature ranges between 0.0 and 1.0 K. The calculated decrease of the average ambient temperature per 0.1 of albedo change varies between 0.0 and 0.61. In Fig. 1, the existing data concerning the possible albedo change and the corresponding decrease of the average ambient temperature are plotted. All data given in Millstein and Menon (2011) are also included. As shown, data correlate quite well in a linear regression given below indicating that an albedo change of 0.1 in urban areas decreases the average ambient temperature by 0.3 K:

$$\text{ATD} = a\,\text{ALBIN} \tag{1}$$

where a = 3.11, ATD is the average temperature decrease and ALBIN the albedo increase ($0 < \text{ALBIN} < 1$). The R^2 of the regression is equal to 0.85.

The calculated relation between the possible albedo change and the average ambient temperature decrease is slightly higher to the one given in Synnefa et al. (2008) for Athens, Greece ($2.4 < a < 2.85$). This is logical as the Athens study considered only reflective roofs and not a general albedo change. In parallel, it is slightly lower than the one calculated in Menon et al. (2010) between the albedo change and the average urban surface temperature.

The calculated reduction of the peak ambient temperature ranges between 1 and 3.5 K. The estimated decrease of the peak ambient temperature per 0.1 of albedo change varies between 0.57 and 2.3 K. Fig. 2 plots the existing data concerning the possible albedo change and the corresponding decrease of the peak ambient temperature. A linear relation between the two parameters has been calculated, although the correlation coefficient is not quite high because of the important scattering of the data. It is found that for an albedo change of 0.1 in urban areas the peak ambient temperature decreases by 0.9 K.

2.3. Change of the albedo from a global perspective

Several studies have investigated the issue of the urban albedo change from a global perspective. In Akbari and Matthews (2010) and Akbari et al. (2009a, 2009b), it was considered that an increase of roof and pavement by 0.25 and 0.15 respectively could decrease radiative forcing by

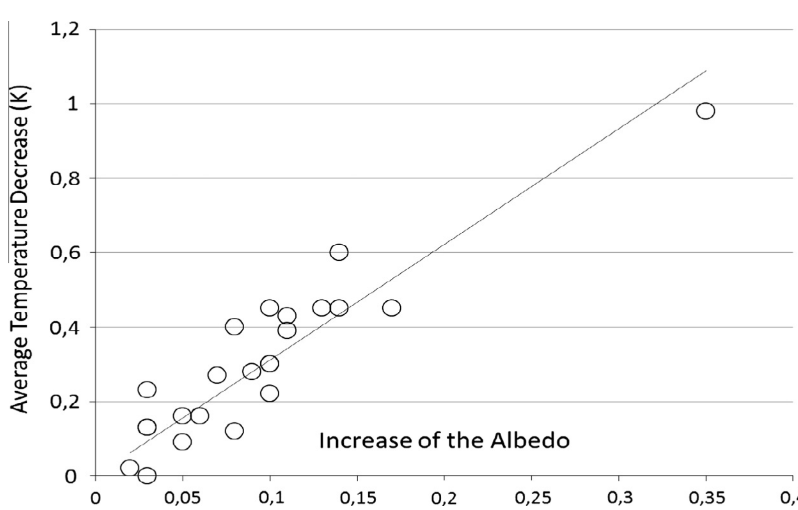

Fig. 1. Correlation between the possible albedo change and the corresponding decrease of the average ambient temperature in urban areas.

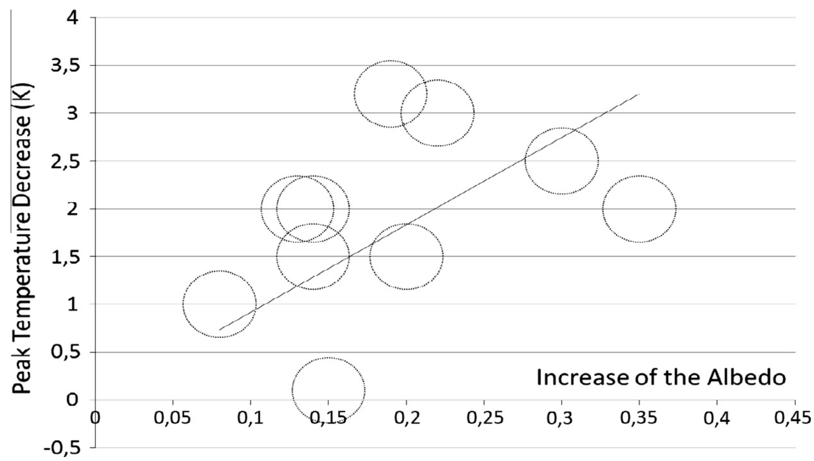

Fig. 2. Correlation between the possible albedo change and the corresponding decrease of the peak ambient temperature in urban areas.

0.15 W/m^2 over the global land area, which is equivalent to one time offset of 44 Gt of emitted CO_2. When the albedo of roofs increases by 0.20, a CO_2 offset of 0.05 tonnes/m^2 is calculated. In a followed up study described in Menon et al. (2010), it was calculated that when the albedo of roofs and pavements increases by 0.25 and 0.15 respectively, the potential CO_2 offset is close to 57 Gt.

In Van Curen (2011), the possible decrease of radiative forcing in California because of the use of cool roofs is calculated. It is estimated that the mean radiative forcing per 0.01 increase of albedo is -1.38 W/m^2. This may result in removing 1.76 million tons of CO_2 emissions in the State. In a more recent study (Akbari et al., 2012), the long-term effect of increasing urban surface albedos has been simulated. It is reported that a long-term global cooling effect of 3×10^{-15} K was calculated for each 1 m^2 of a surface with an albedo increase of 0.01 and this corresponds to an equivalent CO_2 emission reduction of about 7 kg.

3. Mitigation potential of green roofs

Only a few studies aiming to evaluate the heat island mitigation potential of green roofs on a city scale are available. Most of the studies are using simulation techniques based mainly on mesoscale models, and consider roofs of extensive type. Studies are available for New York and Chicago in US as well as for Hong Kong and Tokyo. Important information is also provided by an experimental study in Singapore.

A simulation study aiming to evaluate the mitigation potential of green roofs in Chicago, US, is described in Smith and Roeber (2011). Chicago is a leading city in green roofs technology with more than 50,000 m^2 installed vegetative roofs in 2008. The Advanced Research version of the Weather Research and Forecasting Model (ARW) coupled with an urban canopy model is used (Kusaka and Kimura, 2004). Based on the results given in Rosenzweig et al. (2006), green roofs have been simulated using an equivalent albedo of 0.8. It is found that the use of green roofs provides an important cooling effect to the city. Urban temperatures during 19:00–23:00 were 2–3 K cooler compared to the temperatures simulated without the use of green roofs.

As mentioned previously, a simulation study aiming to evaluate the impact of various heat island mitigation techniques has been carried out for New York city, US (Savio et al., 2006). Details of the study are given above. Extensive roofs using grass were considered. It is reported that the peak ambient temperature at 2 m height for 12:00 LST 14th August 2001, was decreased by 0.37–0.86 K, while the daily average temperature decrease was close to 0.3–0.55 K.

Simulations have been carried out in Tokyo to evaluate the climatic potential of various mitigation techniques including green roofs (Chen et al., 2009). The CSCRC model was used (Chen et al., 2009). Extensive roofs planted with grass were considered. It was calculated that when vegetative roofs were installed in medium and high rise buildings, their potential to decrease ambient temperature at street level is almost negligible.

Similar results are reported in Ng et al. (2012), where the climatic impact of vegetative roofs installed in 60 m height buildings in Hong Kong was evaluated. The simulation study has been performed using the EnviMet tool (Ali-Toudert and Mayer, 2007). Both intensive and extensive green roofs were simulated. It is found that the possible decrease of the ambient temperature at street level in this high rise high density area is almost zero. The study concludes that when the building height to street width (aspect), ratio exceeds 1 (one), the possible cooling benefits at grade is low.

The mitigation potential of green roofs is evaluated by performing measurements of the ambient air temperature at various heights over a vegetated and a conventional roof in Singapore (Wong et al., 2003a). It is reported that the cooling effect of the vegetative roof is restricted by distance from the roof. The maximum temperature difference of the ambient air was 4.2 K measured at 30 cm from the roof at 18:00 h. For higher distances and in particular at 1 m height, the cooling effect is observed during the non peak

Table 3
Characteristics of the existing studies on the mitigation potential of green roofs.

Reference	City	Type of research	Type of green roof	Results
Smith and Roeber (2011)	Chicago, US	Simulation using the Weather Research and Forecasting Model	Extensive type	Urban temperatures during 19:00–23:00 were 2–3 K cooler compared to the temperatures simulated without the use of cool roofs.
Savio et al. (2006)	New York, US	Simulation using MM5	Extensive type	Peak temperatures at 2 m height decrease 0.37–0.86 K, while daily average temperatures decrease between 0.3 and 0.55 K
Chen et al. (2009)	Tokyo, Japan	Simulation using the CSCRC model	Extensive type	Almost negligible impact because of the high of the buildings where green roofs are installed
Ng et al. (2012)	Hong Kong, China	Simulation using the EnviMet tool	Extensive type	Almost negligible impact because of the high of the buildings where green roofs are installed

hours and in particular from afternoon to sunrise of the next day. The study concludes that green roofs may be effective when the building height is lower than 10 m. An almost similar experimental study is reported in Sun et al. (2012). Measurements of the ambient temperature have been performed over a green roof and a height of 2.5 m in Taipei. It is reported that green roofs decreased the ambient air temperature by 0.26 °C in average, while the maximum temperature decrease was close to 1.6 K. Contrary to the results of Wong et al. (2003a), it is measured that the influence of green roofs is more important during the day time.

The main characteristics of the above mitigation studies are summarized in Table 3. It is evident that when vegetative roofs are installed in high or even medium rise buildings, their mitigation potential is almost negligible. The results reported for Chicago and New York have an important difference. The calculated mitigation potential of green roofs in Chicago (2–3 K), is almost 2–3 times higher than that of NY (0.3–0.86 K). In reality, the Chicago study has simulated the impact of green roofs in an indirect way by neglecting latent phenomena and using an equivalent albedo like in the case of a cool roof.

4. Comparing the mitigation potential of cool and green roofs

Reflective and green roofs are among the technologies presenting the highest mitigation potential and both offer important climatic advantages, as previously presented. Various studies have separately assessed the corresponding mitigation potential based on the evaluation of the sensible heat flux reduction from the roof surfaces, which is used as an index of the mitigation potential. However, very few works offer comparative information on the performance of both roof technologies.

Existing works may be classified in three categories. (a) Those using on site measurements to evaluate the thermal phenomena of the roofing systems, (b) Studies completely based on simulation of the phenomena, and (c) Studies based on remote sensing data. Works belonging in (a) and (b) assess the comparative performance of the two roofs systems in a direct or an indirect way. In particular, a direct evaluation of the mitigation potential involves the measurement or calculation of the surface temperature, and/or the calculation of the sensible heat flux reduction from the roof surface. Indirect evaluations are based mainly on the calculation of the energy performance of the roofs or of the possible thermal comfort improvements in buildings. It is evident that high reduction of the cooling needs in a building does not necessarily correspond to a high heat island mitigation potential of the specific roof technology. Decrease of the cooling needs of a building equipped with a cool or a green roof may be the result of the increased insulation potential of the roof and not of the low temperature of the external surface. However, for similar indoor conditions and U values of the roof, the technology that decreases the cooling consumption the most, presents a lower temperature in the external surface, a higher sensible heat flux reduction and very probably a higher mitigation potential.

4.1. Direct comparison of the mitigation potential of cool and green roofs

A direct comparison of the mitigation potential of the cool and green roofs is attempted in Savio et al. (2006). The objective of the study was to evaluate among other the mitigation potential of urban forestry, cool surfaces and green and cool roofs for the city of New York, US. The overall evaluation was performed using the Penn State/NCAR MM5 regional climate model (Grell et al., 1994). Runs were performed for the period of three heat waves during the summer of 2002. The study has calculated the ambient temperature at 2 m height from the ground surface. For the cool roofs, an average solar reflectivity equal to 0.5 was used. It was further assumed that green roofs were covered by grass and had a temperature equal to the street level grass, present in public areas like parks. Simulations have shown that for exactly the same area of cool and green roofs, both systems at 3 PM peak have a city wide temperature impact of 0.4 K. Deeper analysis of the results calculated for the various zones of the city shows that green roofs generally present a quite higher mitigation potential that than of the cool roofs. The economic cost of both systems to achieve a 0.1 F (0.06 °C), of temperature reduction in the city ranged between $233 million for the cool roofs and \$3904 million for the green roofs. As it concerns the cost of the two systems per on peak megawatt reduction, it ranged between \$155 million for the green roofs to \$10 million for the reflective ones.

A second direct evaluation of the comparative performance of cool and green roofs is discussed in Takebayashi and Moriyama (2007). The two roof systems, together with a cement concrete surface, a surface painted with a highly reflective grey paint, and a surface of bare soil were placed and tested in boxes of 1.5–2.0 m^2 cross section, during August and November in Kobe, Japan. The solar reflectance of the cool roof was equal to 0.74. Details on the characteristics of the green roof are not provided. The evaporative efficiency of the green surface is assumed equal to 0.14. The quantity of evaporation was measured to range between 0.008 and 0.018 $g/m^2/s$. Latent heat fluxes from the green roof during the peak period ranged between 400 and 600 W/m^2. Measurements have shown that during the day time in August, cool roofs presented almost 2 K lower surface temperatures than the green roof, while during night it was exactly the adverse. Given that measurements were performed with a radiation thermometer, the surface temperature of the vegetated roof was that of the plant leaves. Low night time temperatures of green roofs are highly influenced by the important latent heat flux of the system. The calculated peak sensible heat fluxes from the cool and green roofs during the day time were estimated close to 153 and 361 W/m^2 respectively, while the corresponding 24 h average sensible heat fluxes were 20 and 2 W/m^2. As mentioned in Scherba et al. (2011), it is meaningful to consider as a heat island mitigation index, the peak sensible flux as it influences highly the air conditioning heating demand, peak electricity loads, etc. However, the night time sensible heat flux is also important as it influences the perpetuation of the heat island cycle. Lower average sensible fluxes from the green roof are due to the negative values calculated during the night period. The results indicate that the heat island mitigation potential of reflective roofs is clearly higher than that of green roofs during the peak daily period where temperatures are higher. The contribution of green roofs is more important during the night period when heat island intensity may be also significant.

A third direct comparison of various mitigation techniques involving a reflective and a green roof as well as a dark roof membrane and photovoltaic panels elevated above various base roofs is discussed in Scherba et al. (2011). The study was performed for several US cities using simulation techniques validated by specific experiments. The considered reflective roof presented a solar reflectivity equal to 0.7, while for the vegetated roof, all the default values of the Energy Plus simulation tool were considered. Description of the simulation routine for green roofs as integrated in Energy Plus is given in Sailor (2008). The study calculated the surface temperature of the various roof systems together with the mean peak daily sensible heat flux and the mean total daily flux. The temperature of the soil was considered as the equivalent surface temperature of the vegetated roof. As it concerns the comparison of the surface temperature of the systems, it is reported that during the night time vegetated roofs present almost 1.5–2.0 K higher temperature than the reflecting ones while during the peak daily period the corresponding surface temperatures are almost equal. The lower night surface temperatures of the reflective roof and the relatively higher surface temperature of the vegetated roof are attributed to the radiative cooling and storage capacity of the ground, respectively. The results seem to be in contrast with the ones given in Takebayashi and Moriyama (2007), where almost the adverse surface temperature conditions were measured. However, as previously mentioned, the considered surface temperature of the green roof in Takebayashi and Moriyama (2007) refers to the one of the leaves while in Scherba et al. (2011) to the temperature of the soil. When the thermal capacitance, the latent heat phenomena and the sky view factor in the surface of the leaves and the soil are taken into account, the observed difference can be easily explained. As it concerns the calculated sensible heat fluxes, reflective roofs present a negative flux during the night period while the flux of the vegetative roofs is positive, as a result of the calculated surface temperatures. The summer peak sensible flux of both systems (in W/m^2) is calculated almost equal while the daily sensible heat flux of the green roofs (in $W\,h/m^2$), was calculated more or less the double of that of reflective roofs. Comparison of the mitigation performance of both systems against a black roof showed that either a reflective or a green roof reduces the peak sensible flux by almost 70%, while the total daily flux of sensible heat is reduced by 80% and 52% when a reflective or a green roof is considered, respectively. The final data of the study clearly indicates that reflective roofs can mitigate urban heat islands more effectively than the considered types of green roofs. However, it has to be underlined that the performance of green roofs highly depends on the characteristics of the plants and the whole configuration of the installed system. In parallel, latent heat phenomena determine highly the thermal conditions of vegetative roofs and any assumption about the water content of the system may alter considerably the thermal performance of this roof technology.

A comparative simulation study assisted by experimental data from existing green roofs is described in (Gaffin et al., 2006). The aim of the study was to identify the equivalent albedo of a cool roof to reproduce the cooling produced by a green roof. Information on the experimental set up is given in Gaffin et al. (2009). Simulations were performed by solving the energy balance equation of the systems. Latent heat flow in the green roof was simulated using a constant Bowen ratio. As Bowen ratio, β, is defined the ratio of sensible to latent heat in the system. This is estimated by fitting simulations to existing experimental data from green roofs collected in Penn State University. Bowen ratios ranging from 0.21 to 0.35, were used, i.e. the latent heat flux in the green roof was almost 3–4 times higher than the sensible one. The considered cool roof was composed by a simple reflective membrane. Thus, the possible thermal storage capacitance of the cool roof was almost not taken into account. Simulations were performed considering cool roofs of various albedos. For the data collected during June 2003, the calculated equivalent albedos of a cool roof system were in the range 0.7–0.85. In particular, it was reported that a cool roof with an albedo around 0.7 has a peak daily surface temperature by 1–8 K higher than that of the green roof, while when albedo increases to 0.85, cool roofs present surface temperatures equal or even 2–8 K lower than that of the green roofs. It is evident that the reported results are not valid for cool roofs presenting an important thermal capacitance. In this case, the surface temperature of the reflective roof is seriously reduced and the equivalent albedo of the green roof is decreasing. In parallel, the assumption of a constant Bowen ratio is questionable, given that the time constant of mass transfer in green roofs is about two orders of magnitude higher than for heat transfer (Castillo Garcia, 2011). Recent research has shown that it is strongly related to weather conditions and vegetation type and that it presents a strong seasonal variation (Jim and He, 2010; He and Jim, 2010). In parallel, as shown in Jim and He (2010) and He and Jim (2010), Bowen ratios are quite higher than the values considered in the present study, ranging between 0.5 and 1.24, although values around 0.12 have been proposed and used in other studies (Martens et al., 2008).

A study described in Simmons et al. (2008) has compared the thermal performance of six types of extensive green roofs against a reflective and a conventional roof. The structure of the green roofs was almost identical across all types and in particular a membrane root barrier, a drainage layer and 100 mm of substrate. The reflective roof was a white membrane of non-reported albedo. Measurements have shown that when ambient temperature reached 33 °C, the surface temperature of the black and white roofs reached 68 °C and 42 °C and the membrane temperatures of the green roofs ranged between 31 and 38 °C.

As previously mentioned, simulations have been carried out to evaluate the impact of various mitigation techniques in Tokyo, Japan (Chen et al., 2009). The study investigated the possible decrease of the ambient temperature at street level when reflective and green roofs are installed in medium and high rise buildings. The albedo of the cool roofs was considered equal to 0.5. Information on the characteristics of the green roofs is not given except that heat release from the green roof is 30% sensible and 70% latent heat. It is reported that cool roofs contribute to decrease ambient temperatures at the street level by about 0.1 K while no significant impact has been calculated for the green roofs.

4.2. Comparing the energy contribution of cool and green roofs

Zinzi and Agnoli (in press), have performed simulations to compare the energy performance of residential buildings in the Mediterranean equipped with conventional, cool or green roofs. The study has not evaluated in a direct way the mitigation potential of the various types of roofs but the energy conservation and the improvement of indoor thermal comfort that result from their use. The cool roof presented a solar reflectivity and emissivity equal to 0.8 and 0.9 respectively while the considered green roof presented the characteristics of a typical Mediterranean planted roof. It is reported that cool roofs provided the highest energy conservation all year round for the center and southern areas of the Mediterranean while in non air conditioning buildings cool roofs delivered the best thermal comfort running. The difference of performance between cool and green roofs was found to be significant; however an important incertitude concerning the impact of water content of the system and the corresponding modeling of green roofs is reported.

A second analysis comparing the energy contribution of green and cool roofs in buildings is given in Susca et al. (2011). The paper describes the results of an experimental study carried out in an office building in NY, USA where a white, a black and a green roof were installed and monitored in parallel for about a year. The black and cool roofs consisted of membranes with albedo values close to 0.05 and 0.6 respectively. The green roof was composed by a 10 cm deep growing medium layer covered with almost 21,000 plants of sedum. The surface of the green roof was close to 1000 m^2 and presented an albedo value around 0.2. Monitoring has shown that during the peak daily period the surface temperature of the green roof was almost 1–8 K lower than the temperature of the white membrane. During the night period, the reflective membrane was 1–5 K cooler than the green roof. The results permit to conclude that the peak sensible heat flow of the green roof should be much lower than that of the reflective membrane and its heat island mitigation potential much greater. Calculations of the contribution of the various roofing systems to the energy consumption of the building, have shown that the installation of a green roof instead of a reflective one results in energy savings ranging between 40% and 110%. It is pointed out that the examined roofing systems presented different insulation properties, and the final U value of the green roof was much higher. It is evident that the results of the specific research are case sensitive and are highly influenced by the characteristics and assumptions of the study and in particular the difference in thermal capacitance and insulation properties of the considered roofing systems.

A third study comparing the potential for energy conservation of cool and green roofs is reported in Saiz et al. (2006). The study was based on the simulation of three roofing systems, a conventional roof, a reflective and a green one for a building in Madrid, Spain. Simulations have been performed using the ESP-r dynamic simulation tool (Hand, 2003). The considered white roof was composed by 'filtron' tiles composed of 4 cm polystyrene protected by a layer of gravels. A white paint was used in the external facade of the roof. The albedo of the roof

Table 4
Characteristics of the existing comparative studies on the mitigation potential of green and cool roofs.

Reference of study	Type of study	Characteristics of cool roofs		Characteristics of the green roof		Results of the study		
Direct evaluation of heat island mitigation potential								
		Albedo	Thermal Capacitance	Albedo	Moisture and Latent heat Characteristics	Potential Reduction of Ambient Temperature	Surface Temperature	Heat Island Mitigation Potential
Savio et al. (2006)	Simulation (MM5)	0.5	Not Given	0.27	Top grass layer 50% moisture	Both systems at 3 PM peak have a city wide temperature impact of 0.4 K.	Not compared	Green roofs seems to have a slight higher mitigation potential
Scherba et al. (2011)	Simulation (Energy Plus) assisted by experimental data	0.7	Low to medium	Not given	The roof irrigationfeature in EnergyPlus was used with a 'smartschedule' which activates an early morning irrigation system if the soil volumetric moisture content falls below (0.15 m^3/m^3).	Not Discussed	During the night green roofs present almost 1.5–2.0 K higher temperature than the reflecting ones while during the peak daily surface temperatures are almost equal	The summer peak sensible flux of both systems was almost equal while the daily sensible heat flux of the green roofs (in W h/m^2), was the double of the reflective roofs Comparison of the mitigation performance against a black roof shown that reflective and green roofs reduce peak sensible flux by almost 70%, while the total daily flux of sensible heat is reduced by 80% and 52% when a reflective or a green roof is considered respectively.
				But LAI=1				Reflective roofs mitigate effectively heat islands than green roofs.
Gaffin et al. (2005)	Simulation (Energy Balance Model), assisted by experimental data	0.7–0.85.	Negligible	0.2–0.3 (Sedum spurium)	Standard Bowen ratios ranging between 0.21 and 0.35.	Not Discussed	Cool roofs with Albedo 0.7 have a peak daily surface temperature by 1–8 K higher than the green roof, while for albedo 0.85, cool roofs present surface temperatures equal or even 2–8 K lower than that of the green roofs	Not discussed
Takebayashi and Moriyama (2007)	Experimental	0.74	high	Not Given (grass)	Evaporative efficiency equal to 0.14. The quantity of evaporation ranged between 0.008 and 0.018 $g/m^2/s$. Latent heat fluxes during the peak period ranged between 400-600 W/m^2.	Not Discussed	During the day time cool roofs presented almost 2 K lower surface temperatures than the green roof while during night it was exactly the adverse	Cool roofs seem to have a much higher mitigation potential during the peak day period. The peak sensible fluxes from the cool and green roofs during the day were close to 153 and 361 W/m^2 respectively. The corresponding 24 h average sensible heat fluxes were 20 and 2 W/m^2.
Simmons et al. (2008)	Experimental	–	Low	Not given	Hand watered to maintain an equivalent minimum 20 mm per week	Not discussed	The surface temperature of the white roof reached 42 °C and the membrane temperatures of the green roofs ranged between 31 °C and 38 °C	Green roofs seems to have a slight higher mitigation potential

Chen et al. (2009)	Simulation, CSCRC model	0.5	High	–	30% sensible, 70 latent losses	0.1 K for reflective roofs, almost zero for green roofs	–	Reflective roofs seems to present a higher mitigation potential than green roofs when installed in high rise buildings.
Indirect evaluation of heat island mitigation potential								
Reference of study	Type of study	Albedo	Thermal capacitance	Albedo	Moisture and latent heat characteristics	*U* value of roofs	Results	
Zinzi et al. (2011)	Simulation (Energy Plus)	0.8-0.9	High	Not Given	Max volumetric moisture content of the soil 0.32 Min volumetric moisture content of the soil 0.01 Initial volumetric moisture content of the soil 0.15	Almost similar U value of cool and green roofs	Cool roofs provide the highest energy conservation all year round for the center and southern areas of the Mediterranean. For non air conditioning buildings cool roofs deliver the best thermal comfort running.	
Susca et al. (2011)	Experimental	0.6	Low	LAI=1.2 0.2	Not Discussed	Green roof has a higher U value than the cool one	During the peak daily period the surface temperature of the green roof was almost 1–8 K lower than the temperature of the white membrane. During the night period, the reflective membrane was 1–5 K cooler the green roof. The installation of a green roof instead of a reflective one results in energy savings ranging between 40% and 110%.	
Saiz et al. (2006)	Simulation (ESP-r)	0.6	High	0.63	Not Discussed	Green roof has a lower U value than the cool one	Green roof decreases the annual building needs for heating and cooling by 1.2% while the white roof contributes to decrease the needs just by 0.4%.	
Ray and Glicksman (2010)	MIT Design Advisor'	0.7	High	Not Given	Not Discussed	Green roof has a lower U value than the cool one	For insulated buildings, cool roofs present a better performance in warm climates while green roofs perform best in cold climates. In non insulated buildings, green roofs perform better than cool roofs because of the higher insulation capacity they offer.	
Sailor et al. (2012)	Energy plus	0.65	Low	Extensive type LAI from 0.5 to 5	Default of Energy Plus	Variable	In warm climates buildings equipped with reflective roofs present a lower net energy consumption than those with a green one, while in colder climates vegetative roofs present a net advantage.	

was set equal to 0.6. An extensive type of green roof was considered, composed of a glass fiber filter layer set on the filtron tiles and then 9 cm of soil substrate and finally the vegetation layer composed by different types of plants characteristic for extensive types. The albedo of the green roof was equal to 0.63, i.e. higher than that of the white roof and almost 2–3 times higher than the measured values for green roofs reported in Gaffin et al. (2009). In parallel, the thermal capacitance of the considered roofing systems were of the same magnitude, while the U value of the green roof was substantially lower than that of the white one. Simulations have shown that the peak surface temperature of the green roof was almost seven degrees lower in the white roof. This probably corresponds to a lower sensible heat flux for the green roof and thus a higher mitigation potential. However, this is a well expected result given the assumptions about the albedos of the green and cool roofs and also the additional contribution of the latent heat in reducing the surface temperature of the green roof. As it concerns the contribution of the considered roofing systems in reducing the energy consumption of the building, it is reported that the green roof decreases the annual building needs for heating and cooling by 1.2% while the white roof contributes to decrease the needs just by 0.4%. This small difference is mainly attributed to the higher insulation capacity of the green roof and the lower calculated surface temperatures on it.

Another comparison of the energy performance of green and cool roofs is given in Ray and Glicksman (2010). The authors have used the simplified calculation tool 'MIT Design Advisor' (MIT, 2010), to estimate the building energy benefits of a cool roof presenting a solar reflectance of 0.7 and of an extensive green roof. Simulations have been performed for various cities in US and Europe. As reported, in insulated buildings, cool roofs presented a better performance in warm climates while green roofs performed best in cold climates. In parallel, in non insulated buildings, green roofs performed better than cool roofs because of the higher insulation capacity they offer.

A very recent comparison of the energy performance of buildings equipped with various types of green roofs and a reflective roof is given in Sailor et al. (2012). The comparison was performed using the Energy Plus building Simulation model for various US cities. Nine types of green roofs characterized by LAI values between 0.5 and 5 and soil depths ranging from 5 to 30 cm were simulated. The reflective roof was equipped with a membrane presenting an albedo equal to 0.65. It was found that in warm climates buildings equipped with reflective roofs present lower net energy consumption than those with a green one, while in colder climates vegetative roofs present a net advantage. Buildings equipped with vegetative roofs of high LAI values, presented a much lower energy consumption for cooling than buildings with a low LAI value, however, in most of the cases, reflective roofs presented a lower cooling consumption than buildings with high LAI green roofs but a higher net energy consumption.

A recent important study described in Mackey et al. (2012), has attempted to evaluate the cooling effect of reflective and green roofs in Chicago, USA, using remote sensing data from LANDSAT collected before and after the installation of the roofing systems over the whole city. It is reported that plots between the increases of the albedo and the temperature change shown by LANDSAT during the test period have a linear regression with a steeper slope and stronger correlations that the plots between the Normalized Difference vegetation Index, NVDI, and temperature change. The results of the study showed that reflective strategies like the use of cool roofs are more effective at cooling the city than green roofs, street trees and green spaces.

A summary of the results of all the reported studies is given in Table 4. Analysis of the published results offer important information but it should not lead to easy and evident conclusions. The characteristic boundary and initial conditions under which the various experiments and simulations have been carried out are quite different, while many important inputs are not reported or are given in a different and non-comparative format. For example, the amount of the latent heat released in green roofs, the major parameter defining their mitigation potential, is sparely reported while the given data on humidity, watering, etc., do not lead to useful and concrete information that could be used in a comparison of technologies.

5. Discussion and conclusions

A fair comparison of the mitigation potential of the considered roofing systems should involve a full knowledge of all the major factors defining their performance. Four categories of parameters may be defined:

(a) Climatological variables: In particular, solar radiation intensity, ambient temperature, ambient humidity, wind speed and precipitation. Solar radiation intensity largely determines the heat storage and surface temperature of the roofs as well as the amount of the heat transmitted to the building and the evaporation. The spectral characteristics of the incoming solar radiation are also important in green roofs canopies where the color, moisture and the structure of the layers vary the transmittance, reflectance and absorptance as a function of the wavelength (Huete, 1988; Jacobsen et al., 1995). Ambient temperature is a key variable and determines the amount of sensible heat released by the roofs. Convective heat flow is a direct function of the temperature difference between the roof and the ambient temperature. As reported in Jim and He (2010), the seasonal sensible heat flux from green roofs is minimum in winter when ambient temperature is low and reaches a maximum during the summer period. In parallel, research carried out in Jim and He (2010) show that extreme values of the sensible and latent heat in green roofs are highly correlated with ambient temperature. Wind speed and atmospheric turbulence define the heat transfer coefficient between the surface and the atmosphere and determine sensible heat flux. Higher wind speeds increase the flux of sensible heat and evapotranspiration from the green roofs. Higher wind speeds accelerate the transfer of water vapor from the soil or foliage to the atmosphere and contribute to increase the rate of evapotranspiration (Tsang and Jim, 2011). As measured in Tabares-Velasco and Srebric (2011), when the air speed increases from 0.1 m/s to 1 m/s, evapotranspiration in a green roof increases by 10–30%. According to Jim and Peng (2012) wind speed is highly correlated with surface temperature in green roofs. Atmospheric relative humidity defines the vapor pressure gradient between the air and the green roof. High relative humidity suppresses the evapotranspiration from the green roofs and reduces latent heat flux (Jim and Peng, 2012). Finally precipitation increases the moisture of the soil in green roofs and determines the amount of the latent heat flux. Precipitation is highly correlated with extreme values of latent heat in green roofs (Jim and He, 2010).

(b) Optical Variables and in particular the albedo to solar radiation and the emissivity of the roofing systems while in green roofs the absorptivity of the plants define at large the shielding effects in the roof. The albedo to solar radiation of reflective roofs is the key variable defining its thermal budget. High albedos decrease the absorbtance and the accumulation of heat in the roof and decrease its surface temperature which corresponds to lower sensible heat fluxes and higher mitigation potential. The emissivity of the roofs defines their ability to dissipate heat through emission of infrared radiation. Higher emissivity values correspond to lower surface temperatures and higher mitigation potential. The typical value of emissivity for a green roof ranges from 0.9 to 0.95, depending on plants type (Gates, 1980). Shielding effects in green roofs because of the presence of green foliage determine the amount of heat absorbed by the roof structure. Plants absorb radiant energy to enhance biological photosynthesis preventing absorption of the radiation by the soil and the roof structure. As already mentioned, the higher the water leaf content the higher the absorbtance of the visible radiation. As mentioned in Jim and He (2010), shrubs present a high shield effectiveness compared to grass. According to Lazzarin et al. (2005) the average absorbed solar radiation by the greenery is close to 23%. The effective albedo of green roofs is highly determined by the density of the green spaces on its surface. Measurements of surface temperature in green roofs reported in Niachou et al. (2001), show that in places dominated by thick dark green vegetation present surface temperatures almost 10 K lower than places covered by sparse vegetation. Measurements performed in Wong et al. (2007) show that the surface temperature in sparsely covered by vegetation areas was up to 73.4 °C during the day period. In parallel, it is reported that when the substrate is dry its temperature can exceed the surface temperature of the exposed roof. Various studies have shown that vegetation has to be dense to produce an important cooling effect (Bowler et al., 2010; Chang et al., 2007; Potchter et al., 2006).

(c) Thermal variables: The thermal capacity of the roofs as well as their U value are key thermal parameters defining their performance. Increased thermal capacity of the roofs leads to a maximization of the stored heat reducing peak surface temperatures and decreasing the sensible heat flux. According to He and Jim (2010), the daytime heat storage in the green roofs ranges between 350 and 500 W/m^2 on an hourly basis. During the night period negative values around 60 W/m^2 are recorded. The overall heat transfer coefficient of the roof defines the heat transferred to the building through the roof and determines its energy load. It influences the mitigation potential of the roof in an indirect way, as it is part of the overall thermal balance equation of the roof. Many studies have evaluated the total flow of heat to the building through the green roof. Results reported in Lazzarin et al. (2005), Onmura et al. (2001) and Tang and Jiang (2009), show that the total heat flux entering the building below the green roof was reduced by 60%, 50% and 73% respectively, compared to a conventional concrete roof without green roof irrespective of the weather conditions. The impact of soil depth of the green roofs and the corresponding U value of the roof is found to be very important concerning the energy consumption of the buildings (Sailor et al., 2012). Estimated U values of green roofs with a shallow substrate, varies between 1.17 and 2.70 $W/m^2/K$ (Wong et al., 2003b; Tabares-Velasco and Srebric, 2009; Bell and Spolek, 2009)

(d) Hydrological variables: In particular all parameters defining latent heat phenomena in green roofs. Latent heat losses of evaporation are associated to the water vapor from the plants and the soil of the green roof and equal the thermal energy gained by the phase transition of the water molecules (from the liquid to the vapor phase). In soil, the latent heat is transferred by diffusion of vapor in pores. The transfer of heat depends mainly on the water content and temperature. The soil moisture content should be always above the wilting point of the soil, and below the soil field capacity (Palomo and Del Barrio, 1998). When the moisture content is below the wilting content, water is completely unavailable to the plants while when it exceeds the soil field capacity it may damage the roots. The transfer of water vapor between the soil and the ambient air depends on the vapor pressure at the soil surface, the vapor pressure at the canopy layer and the corresponding pressure of the ambient air. Evapotranspiration in the plants surface involves three specific processes, (a) the water evaporation inside the leaves, then (b) the diffusion of vapor to the surface of the leaves and (c) the transport of the vapor from the surface of the leaves to the air. The energy flux related to the evaporation of water from the leaves depends mainly on the vapor pressure at the leaf surface, the corresponding vapor pressure in the canopy and the internal resistance to the vapor transfer in the canopy. Information on the internal resistance can be found in Stahghellini (1987) and Farquhar and Sharkey (1981). Detailed models to simulate the vapor transport in green roofs are given in Palomo and DelBarrio (1998) and Banna et al. (2002). Sensitivity analysis performed in Hodo-Abalo et al. (2012) and results reported in Sailor et al. (2012), on the magnitude of evapotranspiration from a green roof has concluded that the Leaf Area Index is the key parameter defining evaporation losses. It is reported that Evapotranspiration losses during the peak period ranges between 250 and 550 W/m^2 for LAI indexes of 2 and 7, respectively. Typical daytime latent fluxes reported in Takebayashi and Moriyama (2007) and Scherba et al. (2011) were between 250 and 400 W/m^2.

(e) Although all parameters identified previously play an important role on the performance of both roofing systems, it is evident that the solar albedo and the released latent heat are the key variables that determine the mitigation potential of the systems. During the peak summer period and when solar radiation intensity is close to 900 W/m^2, green roofs absorb almost 300–550 W/m^2 more that cool roofs. This is based on the assumption that the solar albedo of cool roofs varies between 0.6 and 0.8, while in green roofs between 0.2 and 0.3 (Jim and Tsang, 2011). Considering an equal heat accumulation in the structure of the roofs and heat flow through the roof to the building, green roofs have to dissipate the excess heat through evapotranspiration and release of latent heat in order to present a similar energy budget with cool roofs.

(f) Various theoretical and experimental studies have evaluated the amount of latent heat released by green roofs during the peak period. The estimated values vary considerably as a function of the boundary conditions in the experiment and mainly as a function of the water content in the roof (Ayata et al., 2011). According to Takebayashi and Moriyama (2007), the latent heat flux from a green roof during August in Japan varied in the range of 300–400 W/m^2, while in Scherba et al. (2011) the typical daytime latent flux was close to 250 W/m^2. Simulations reported in Hodo-Abalo et al. (2012) for the peak period show that the latent heat flux of green roofs varies between 250 and 270 W/m^2, for $LAI = 2$ and Biot numbers varying between 6 and 22. Results of a sensitivity analysis regarding LAI show that for $LAI = 4$ and $LAI = 7$ the latent flux increases up to 370 and 550 W/m^2, respectively. Analysis given in Lazzarin et al. (2005), estimates that for a solar radiation flux close to 900 W/m^2, the latent heat flux form a dry or wet green roof would be close to 110 W/m^2 and 230 W/m^2, respectively. Other data reported in Feng et al. (2010) for an extensive green roof with $LAI = 4.6$ show that during the peak summer period and for a solar radiation intensity close to 900 W/m^2, the latent heat flux from the green roof was close to 600 W/m^2. Results reported in Rezaei (2005) and Berghage et al. (2007) show that evapotranspiration heat flux from an extensive green roof during the

Table 5
Latent heat release by green roofs according to various studies.

Reference	Characteristics of green roof	Peak solar radiation intensity (W/m^2)	Latent heat (W/m^2)
Takebayashi and Moriyama (2007)	Lawn	900	300–400
Hodo-Abalo et al. (2012)	For $Bi = 8.61$		
	$LAI = 2$	520	250
	$LAI = 3$	520	300
	LAI-4	520	350
	$LAI = 5$	520	450
	$LAI = 6$	520	500
	$LAI = 7$	520	560
Lazzarin et al. (2005)	$1.1 < LAI < 1.5$		
	Dry Roof	900	110
	Wet Roof	900	230
Feng et al. (2010)	Extensive, $LAI = 4.6$	900	600
Rezaei (2005 and Berghage et al. (2007)	Extensive	–	350
(10)	Grass	1000	100
	Shrubs	1000	150
Alexandri and Jones (2007)	Grass	500–800	26–593
Jim and He (2010)	Turf Grass	800	250
	Ground cover herb	800	280
	Shrubs	800	400

period of the peak solar intensity was close to 350 W/m^2. Simulations of the latent heat released by a green roof with grass and shrubs reported in He and Jim (2010) considering that solar radiation intensity is close to 1000 W/m^2, show that it ranges between 100 and 150 W/m^2. In parallel, a similar research reported in Jim and He (2010) shows that during the peak summer period the latent heat from green roofs ranges between 250 and 400 W/m^2 as a function of the plants used, while in Alexandri and Jones (2007), it is calculated that latent heat from green roofs varies between 26 and 593 W/m^2. Details of all the above studies are given in Table 5.

Taking into account all data and results presented previously and summarized in Tables 1 and 2, the following conclusions can be drawn:

(a) When the albedo of the reflective roofs is equal or higher than 0.7, then for all three direct and the one indirect comparative studies reported, cool roofs present a much higher heat island mitigation potential than green roofs during the peak period. However, in all studies, the comparison has been performed against green roofs of extensive type and low LAI. As shown in Table 5, the peak latent heat in those roofs ranges between 100 and 250 W/m^2 and may not compensate the reflective benefit of cool roofs that is higher than 400 W/m^2. It is considered that the rest of the terms of the heat balance are almost similar for both roofs.
(b) Green roofs may present a similar or higher mitigation potential during the peak period, when latent heat losses exceed more or less 400 W/m^2. According to the data given in Table 5, this is possible for very well irrigated vegetative roofs presenting a LAI higher than 4 or 5 and for quite dry climates.
(c) Climate plays a very important role on the mitigation potential of cool and green roofs. In sunny climates, reflective roofs present an important advantage while in moderate and cold climates vegetative roofs seem to present higher benefits.
(d) Weatherisation is a serious problem for reflective roofs. Experimental data reported in Miller et al. (2002), Cheng et al. (2001, 2012) and Berdahl et al. (2002), suggests that the reflectance of roofs decreases because of the dust load, ultraviolet radiation, microbial growth, acid rain, moisture penetration and condensation, wind and biomass accumulation. Other research shows that black carbon particles, known as soot particles, is the primary cause of reflectance loss. According to Bretz and Akbari (1997), the albedo of cool roofs decreases averaging 0.15 during the first year and may be restored to within 90% of its initial value after washing. In this case, well irrigated green roofs of extensive type presenting a LAI > 1.5 may present an equivalent mitigation potential with cool roofs of an initial albedo around or higher than 0.7.
(e) Comparative studies considering an albedo of the reflective roofs around 0.5–0.6 are very limited and show a slight better performance of the green roofs. This is very probable when a well irrigated green roof is considered and the thermal capacity of the reflective roof is quite limited and the climate is not very humid. For the specific zone of values, the difference of the mitigation potential of the two roofing systems may be not very important.
(f) Studies considering albedo values lower than 0.5 and higher than 0.3 are not available. On the contrary many studies have compared the performance of green roofs against conventional roofs presenting albedo values lower than 0.3. In all cases the performance of the green roofs was found much higher than that of the conventional roofs.
(g) When reflective or green roofs are installed in high rise buildings, the expected climatic impact and mitigation potential is very limited.

Facing the heat island phenomenon asks for the development and application of efficient mitigation technologies. Reflective and green roof technologies have achieved a very high degree of maturity and offer a very significant option for urban climatic improvements. It is evident that future research and development is necessary in order to develop new and more efficient materials and procedures as well as new advanced demonstration and large scale application projects.

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