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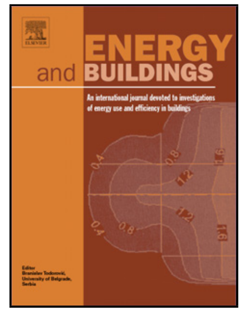

Title: Dynamic analysis of the heat released by tertiary buildings and the effects of urban heat island mitigation strategies

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Dynamic analysis of the heat released by tertiary buildings and the effects of urban heat island mitigation strategies

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HIGHLIGHTS

- The analysis of the buildings' contribution to UHI is investigated
- The heat released by outer surfaces and HVAC system is analyzed
- A comparison of the effects of UHI mitigation strategies is carried out
- Highly insulated envelopes do not reduce the heat released during summer
- Outer surfaces contribute much more than the AC system to the UHI

KEYWORDS

Urban heat island; Heat released by buildings; Cool roofs; Building energy model.

ABSTRACT

This study presents a comprehensive approach for calculating buildings' energy contribution to the formation of urban heat island (UHI). For this purpose, the heat released by building envelope and HVAC system has been taken into account, while longwave radiation to the sky has been excluded from the calculation, as it is not so relevant to the UHI effect.

Several strategies to minimize the UHI phenomenon and their effects on the heat released have been considered along the whole-year period. An existing educational building has been selected as case study. The selected building is considered representative for a wide range of tertiary buildings with an intermittent operation mode. Results have been obtained by dynamic simulation models, which have been validated with measured indoor air temperature data.

Despite a moderate reduction of the energy contribution to the UHI effect during winter, which is commonly considered unfavorable, the effectiveness of cool coating application in reducing the heat released during summer has been clearly demonstrated. On the other hand, it was found that a higher level of envelope insulation is not yielding a significant reduction of the heat released, especially during summer.

Introduction

Anthropogenic heat strongly contributes to the formation of the effect of the urban heat island (UHI), which consists in the presence of higher urban temperatures compared to the adjacent suburban and rural areas [1]. Sources of anthropogenic heat include buildings, industrial processes and transportation [2]. Many causes, such as release of anthropogenic heat, air pollution, excess storage of heat by urban geometries, lack of vegetation, and reduced ability of the emitted infrared radiation to escape in the atmosphere, bring to a positive thermal balance and higher temperatures in urban areas [3][4].

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The UHI formation is a complex phenomenon, depending on urban canopy, meteorological condition and territorial topography [5]. However, the existence of a correlation between the heat released by buildings to the urban environment and the level of the formation of UHI can be expected. This correlation also forms the basis of a recent study of Capucci et al. [6], proposing an index which describes concisely the potential of UHI mitigation brought by urban regeneration. Moreover, Bonamente et al. [7] propose an analytic model representing UHI effect in the built environment related to weather conditions and geometrical and optical properties of urban areas surfaces.

In previous studies, the attention has been generally focused on the evaluation of UHI effects on indoor thermal environment and building energy performance [8] [9] [10] [11] [12]. However, only a few studies have investigated the total energy released by buildings, especially considering the effect of different factors involved in the phenomenon, such as convective heat transfer [13], sensible heat flux from external surfaces [14], net infrared heat flow to the sky [15] or external surface properties [16].

Building fabric materials absorb solar and infrared radiation. The collected heat is released by convection to the atmosphere and by longwave radiation to other surfaces or to the sky, increasing ambient temperature [17]. Consequently, thermal and optical properties of the building construction materials, such as thermal mass or surface albedo, are strongly related to the energy needs and the energy released by buildings to the environment [18].

With regard to the summer period, the main heat input to be counterbalanced by air conditioners is due to solar gains. Summer overheating may occur through either transparent elements or opaque ones. The gains through opaque elements, however, while lower than those through transparent elements in terms of heat rate per unit area, can have a similar impact on the overall summer behavior of a building as a result of the large irradiated area of roofs and walls [19]. Thermal cycles induced by solar radiation at the outer surfaces can be substantially damped through the thickness of roofs and walls. This effect is generally achieved by giving roofs and walls an adequate level of either thermal insulation or thermal inertia. However, by using an outer coating with high solar reflectance, *i.e.* which reflects a high fraction of incident solar radiation, it is possible to dampen the thermal cycles induced by solar radiation directly at the outer surface rather than through the thickness [20]. In the technical nomenclature such type of coating is identified with the terms of cool roof or cool color. In the study of Pisello and Cotana [21] it is shown that, by the application of an innovative cool roof system on a residential building, the external surface temperature of the roof is reduced by approximately 15–18°C during summer and by approximately 2–3°C during winter. Moreover, Pisello et al. [22] demonstrated that during winter season the roof outer surface temperature is mostly determined by meteorological conditions, while the outer surface optical properties do not modify significantly the roof thermal performance. Besides traditional cool materials, Rossi et al. [23] found that the application of retroreflecting coatings on surfaces in urban areas presents a considerable cooling potential.

On a wider scale, cool coatings application on building external surfaces in urban areas leads to the reduction of air temperature, because of lower release of energy [24]. Other studies [25] demonstrate that large-scale increases in surface albedo can effectively counteract the urban heat island intensity in most of the urban areas. Akbari and Matthews [26] demonstrated the long-term effects of surface albedo modification on the reduction of global temperature. The study of Cotana et al. [27] presents a methodology that quantifies the mitigation of Global Warming, in terms of tCO_{2eq}, obtained through the enhancement of earth's albedo.

The present work aims at evaluating the contribution of tertiary buildings to UHI, in terms of heat released, and its reduction achieved by several countermeasures. In particular, this paper investigates the contribution on UHI effect given by educational buildings, such as

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university buildings, characterized by variable occupancy and high indoor air quality demand.

This study quantifies the energy released by the building, focusing on the impact of several factors, such as radiative and convective energy transferred from building surfaces and air conditioning system.

Several strategies to minimize the UHI effect, above all the use of cool materials on external building surfaces, have been considered and their effects on the total energy released by the building and on the external surface temperature profiles are obtained through energy modeling simulation.

Calculation

Energy modeling and calculation

The total energy released by an existing structure, selected as representative of the educational building type and other tertiary buildings, is calculated along the whole year and is determined by considering the total (convective and radiative) heat flow from the building external surfaces and the heat released to the environment by the HVAC system.

The simulations have been carried out using the TRNSYS 17 dynamic thermal modeling software [28].

The meteorological data used in the simulations were collected by the University of Modena and Reggio Emilia weather station. The hourly weather data include global radiation on horizontal, dry bulb temperature, wind speed and relative humidity [29].

In order to evaluate the contribution of the case study to the UHI, only the heat released by the building envelope to the surrounding environment has been considered, taking into account the sky view factors and excluding the longwave radiation from the building's external surfaces to the high atmosphere. In fact, the net infrared heat flow, always outgoing from the external surfaces towards the high levels of the urban atmosphere [15], does not contribute significantly to the formation of the UHI; as a matter of fact, the UHI effect is stronger in clear sky conditions, even if the upward infrared radiation by surfaces to sky is not trapped by cloud covers [30].

The hourly indoor air temperature measurements were used to calibrate the dynamic simulation model of the building . During the measurements the building was unoccupied for a period of two weeks, in order to better capture the thermal dynamics of the envelope. Once the building model was calibrated, internal gains were defined for each thermal zone by considering the characteristics of actual systems and schedules.

Case study

In this study, the Interdepartmental Scientific Library of the University of Modena and Reggio Emilia has been selected for the comparative analysis. Tertiary buildings, such as the educational buildings, are characterized by variable occupancy, high indoor air quality demand, high level of temperature and lighting comfort. The need to meet these requirements implies a high energy consumption.

The library building is located in the surrounding of the city of Modena and it was built in 1998. The building has 2 storeys, amounting to a total building height of about 12 m. The building contains a main reading room, several offices, two archives, meeting and technical rooms (see Figure 1). Table 1 shows the most important geometrical characteristics of the selected building.

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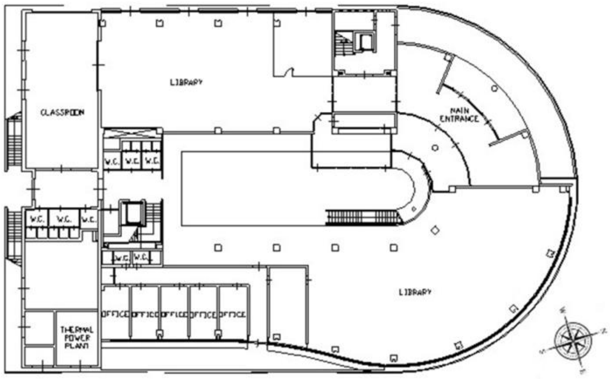
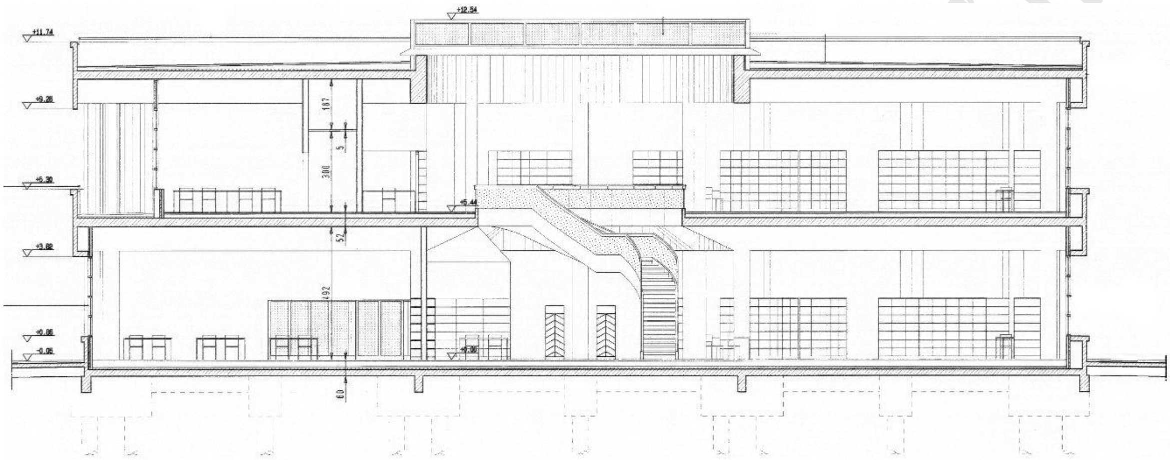


(a)



(b)

(c)

Figure 1. Plan (a), section (b) and view (c) of the building.

Table 1. Main geometrical characteristics of the building

Floor surface [m^2]	2200
Opaque vertical surfaces [m^2]	1925
Transparent surfaces [m^2]	718
Gross volume [m^3]	18313

The main building envelope components are: concrete and light insulated external walls (U_w = 0.52 W/(m^2 K)), a non-insulated roof (U_r = 1.32 W/(m^2 K)) with north-oriented windows, and double glazed windows (U_g = 2.83 W/(m^2 K), g = 0.45). The external concrete walls layer is gray, while the roof waterproof coating is dark. The thermal properties of the

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envelope components of the current building are shown in Table 2 and Table 3 and in Figure 2.

(a)

(b)

Figure 2. Particulars of the envelope. (a) Walls, (b) roof.

The HVAC system, composed by two gas boilers, a refrigeration unit and several air handling units, is active only during daytime, from 8:00 to 18:00, and only during working days. The summer period extends from June 1st to September 15th and the set-point temperature is 26°C, while the winter period extends from October 15th to April 15th and the set-point temperature is 20°C. Mechanical ventilation is used to provide 1.5 air changes per hour.

Internal gains, such as lighting, equipment and occupants, are defined according to the conventional opening hours of the building (from Monday to Friday, from 8:00 to 18:00). The library has a total capacity of 257 available seats and the daily visitors are estimated to be around 500.

Description of the simulation cases

The above mentioned library building has been used as the base-case model (Case B, "Current Building") for the comparative analysis. Simulations have been performed for the following cases:

- Case B: current condition of the building, with dark waterproof coating on the roof;
- Case CB: cool coating on the roof ($\alpha_{sol} = 0.25$);
- Case IB: additional insulation layer for the roof and opaque vertical surfaces, vertical windows with lower thermal transmittance value and the original dark waterproof coating on the roof ($U_w = 0.27$ W/(m^2 K), $U_r = 0.26$ W/(m^2 K), $U_g = 1.4$ (W/m^2 K));

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- Case CIB (CB+IB): cool coating on the roof (α_{sol} = 0.25), additional insulation panels for the roof and opaque vertical surfaces, vertical windows with lower thermal transmittance value (U_w = 0.27 W/(m^2 K), U_r = 0.26 W/(m^2 K), U_g = 1.4 W/(m^2 K));

Table 2. Description of the parameters varied in the simulation cases

Cases	**Current Building (B)**	**Building with Cool Roof (CB)**	**Building with Insulation (IB)**	**Building with Cool Roof and Insulation (CIB)**
α_{sol} *(roof)*	0.90	0.25	0.90	0.25
U_w [W/(m^2 K)]	0.52	0.52	0.27	0.27
U_r [W/(m^2 K)]	1.32	1.32	0.26	0.26
U_g [W/(m^2 K)]	2.83	2.83	1.40	1.40

Table 3.Thermal properties of the layers of the building envelope

Opaque vertical surfaces											
Cases A, CB	Layers	s [m]	λ [W/(m K)]	c [kJ/(kg K)]	ρ [kg/m^3]	**Cases IB, CIB**	Layers	s [m]	λ [W/(m K)]	c [kJ/(kg K)]	ρ [kg/m^3]
	Concrete panel	0.24	0.51	1	1400		Concrete panel	0.24	0.51	1	1400
	Insulation	0.05	0.04	1.4	10		Insulation	0.12	0.04	1.4	10
	Gypsum plaster	0.01	0.35	1	1200		Gypsum plaster	0.01	0.35	1	1200
	U [W/m^2 K]	0.52					U [W/m^2 K]	0.27			
Roof											
Cases B, CB	Layers	s [m]	λ [W/(m K)]	c [kJ/(kg K)]	ρ [kg/m^3]	**Cases IB, CIB**	Layers	s [m]	λ [W/m K]	c [kJ/(kg K)]	ρ [kg/m^3]
	Bitumen Waterproof coating	-	0.17	1	1200		Bitumen Waterproof coating	-	0.17	1	1200
	Concrete slab	0.30	0.51	1	1400		Concrete slab	0.30	0.51	1	1400
	Gypsum plaster	0.01	0.35	1	1200		Insulation	0.12	0.04	1.4	10
							Gypsum plaster	0.01	0.35	1	1200
	U [W/m^2/ K]	1.32					U [W/m^2/ K]	0.26			

Monitoring set-up

The library building is equipped with a monitoring system for measuring the indoor air temperature. The temperature is measured by data loggers with embedded thermistors, with accuracy of ± 0.5°C, positioned at 1.5 m height (see Figure 3). The indoor air temperature measurements were collected in 30 min intervals and averaged to hourly data. The overall monitoring period covers February to September 2013.

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Figure 3. Pictures of a temperature sensor and its position.

Results and discussion

Statistical analysis were performed to evaluate the discrepancies between simulated (Case B) and current building energy performance. The Normalized Mean Bias Error (NMBE), and the Coefficient of Variance of the Root Mean Square Error (CV(RMSE)) were used for the analysis. Respectively, the NMBE and the CV(RMSE) of the hourly indoor air temperature were 2% and 5%. The results show that the selected indexes are in agreement with the tolerance range [27] and the model is considered representative of the actual energy performance.

Starting from Case B, the other simulation cases were obtained by modifying several parameters, as shown in Table 3. The results show that the heat released by the selected building significantly decreases by decreasing the solar absorptance of opaque surfaces, especially thanks to the application of cool coating on the roof (Case CB and Case CIB).

The application of cool coating on opaque vertical surfaces presents values of heat released very similar to those obtained with non-treated opaque vertical surfaces. Consequently the results related to the application of cool coating on vertical surfaces have been excluded from the analysis.

Figure 4 shows the heat release to the ground level atmosphere by the HVAC system and by the building envelope, excluding the longwave radiation to high atmosphere.

During the summer period the heat released by the air conditioning system is assumed to be equal to the heat extracted from the building envelope, including the air treatment, and the energy consumption of the AC system. To assess the overall energy consumption of the AC system, an average energy efficiency ratio (EER) of 2 is considered.

During the winter period the heat released by the HVAC system corresponds to the heating system energy losses, excluding a portion of recovered distribution losses. An overall efficiency of 73% is considered for the heating system.

The simulation results illustrate that during the summer period the heat released by the surfaces is much higher than the heat released by the AC system, especially for Case B and IB (i.e. average of about 77%). The results also demonstrates that improving thermal transmittance values of the building envelope (Case IB) causes a significantly lower UHI mitigation benefit (i.e. less than 1%) compared to the application of cool coatings on the roof (Case CB), which leads to a heat released reduction of about 63%. By the application of cool roof (i.e. Case CB and Case CIB), the energy released by the building presents the highest reduction. Moreover, the heat released by the AC system also reduces up to 20% referred to

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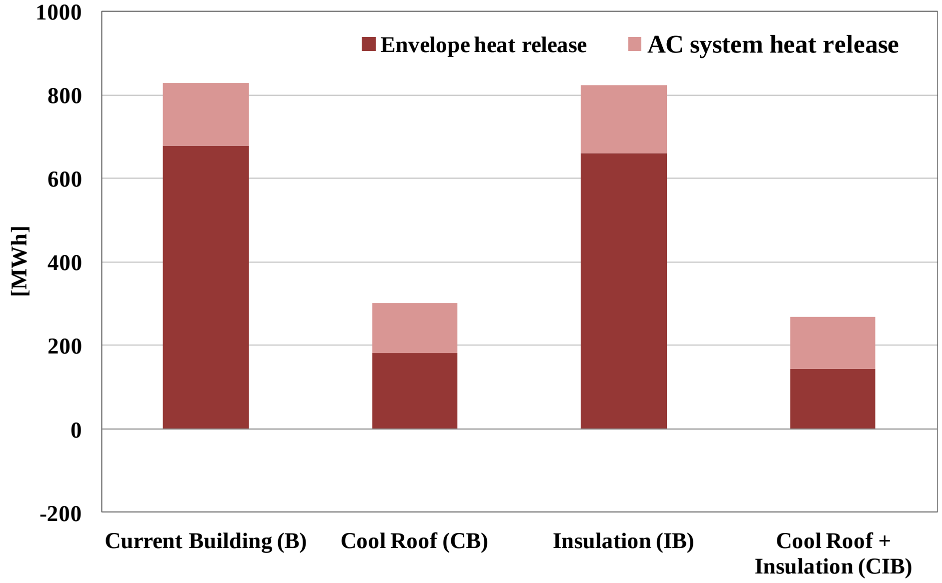
Case B. The application of insulating layers combined with cool coatings (Case CIB) further reduces the total heat released by the building and the AC system.

During the winter period, with low absorptance coatings (Case CB and Case CIB) the heat flux from the building envelope to the ground level atmosphere excluding the longwave radiation is negative, thus reducing the UHI effect (see Figure 4b). A typical objection against cool coatings application concerns their winter behavior, as this outer finishing, by reducing the heat released, could thus reduce the external temperature and increase energy needs of the surrounding buildings. However, the comparison between the summer and the winter period balance shows that the reduction of the contribution to UHI due to the cool roof application in summer is significantly higher (i.e. about 45%) than the reduction achieved in winter (i.e. about 25%). A similar situation is found for Case CIB.



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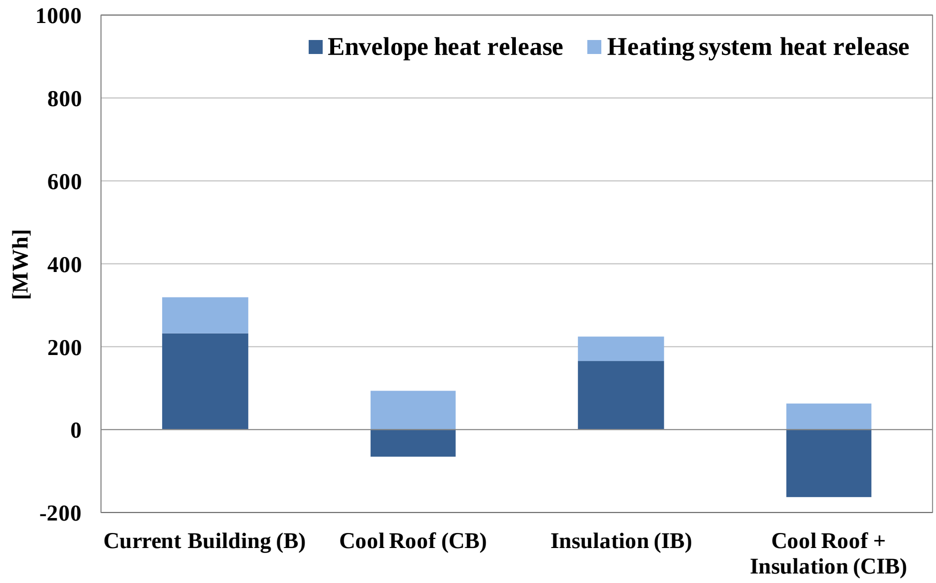

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(b)

Figure 4. Total heat released to environment in the summer (a) and the winter (b) periods. Positive values for heat transferred to the surrounding atmosphere at ground level

Figure 5 shows the heat released by the envelope to the surrounding atmosphere at ground level, excluding the longwave radiation from the building's external surfaces to the high atmosphere. Case B and IB present the highest values of the heat released by the building envelope during the summer period. Actually, the mere application of an additional insulation layer on roof and opaque vertical surfaces (Case IB) is not reducing significantly such heat released (i.e. average reduction of about 5% for Case IB with respect to Case B). On the contrary, Case CB and Case CIB, present a significant reduction of the heat released by the building envelope in summer with respect to Case B (i.e. average of about 80% and 90% respectively).

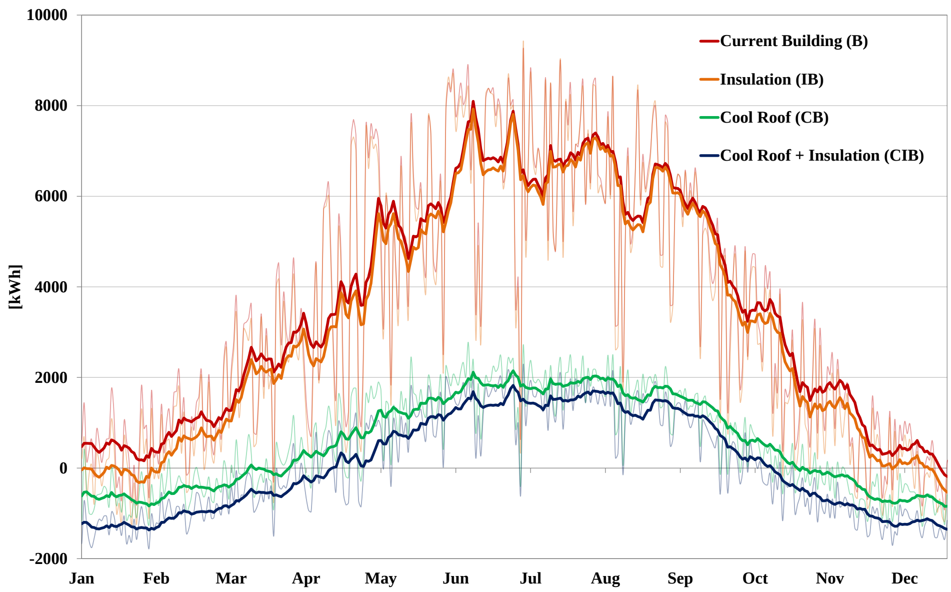

Figure 5. Envelope heat release. Daily average (transparent lines) and 15-day moving average trendlines (thick lines).

Figure 6 shows a comparison between Case B and Case CIB in terms of the overall energy released by the building envelope including longwave radiation to the sky, which in turn does not contribute significantly to the UHI effect. The graph shows that, especially during the winter period, the energy released to the sky by longwave radiation is not negligible in comparison to the energy released to the surrounding atmosphere at ground level by the envelope. This result shows that it is important to exclude the longwave radiation to sky to evaluate accurately the contribution to the UHI.

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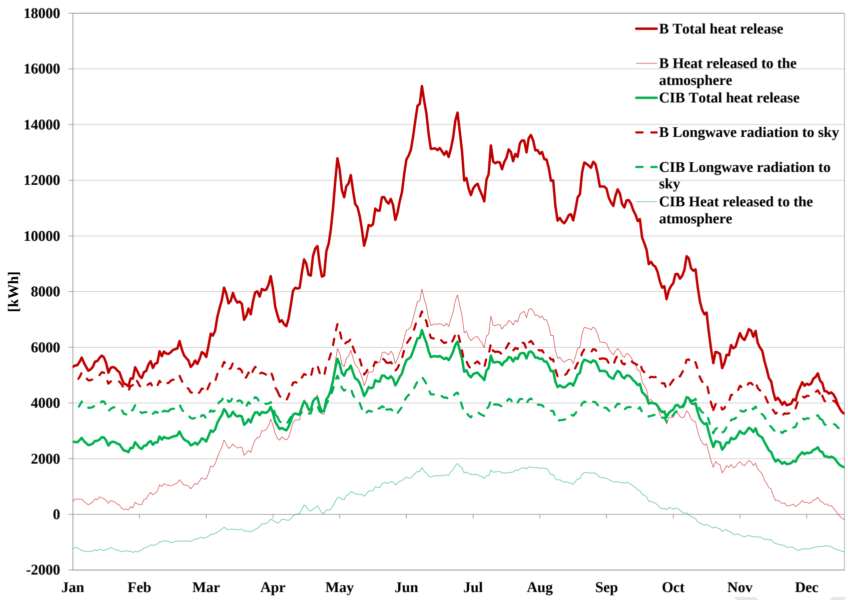

Figure 6. Heat released by building envelope for the Cases B and CIB. Total heat released (thick lines), heat released to the surrounding atmosphere at ground level (transparent lines), longwave radiation to the sky (dotted lines). 15-day moving average trendlines.

As can be seen in Table 4 and Figure 7, representing the heat released due to HVAC system, the results show again the effectiveness of the application of cool materials in the mitigation of UHI effect during the summer period.

Table 4. Average variations of heat released due to HVAC system with respect to Case B during summer and winter period.

	CB	IB	CIB
Summer	-20%	12%	-21%
Winter	17%	-42%	-35%

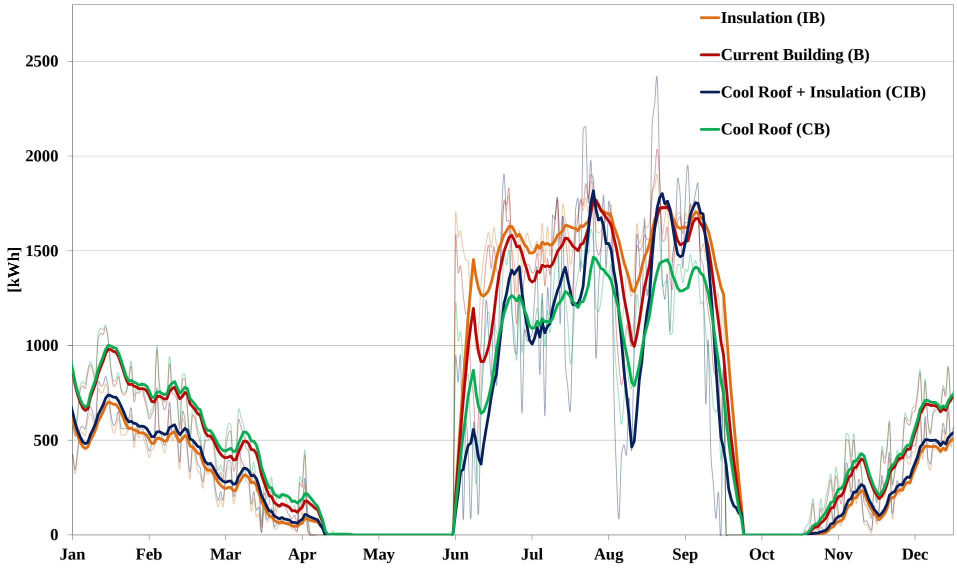

Figure 7. Heat released due to HVAC system. Daily average (transparent lines) and 15 days moving average trendlines (thick lines).

Figure 8 shows the energy released by the whole building, *i.e.* by both the envelope and the HVAC system. The analysis demonstrates that during the winter season the

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application of cool coatings on the roof (Cases CB, CIB) reduces the contribution to the UHI with respect to Case B. However, this negative effect is low and almost negligible when compared with the benefits in summer, demonstrating the effectiveness of the application of cool coating on roof surfaces (case CB), possibly combined with an insulating layer (case CIB).

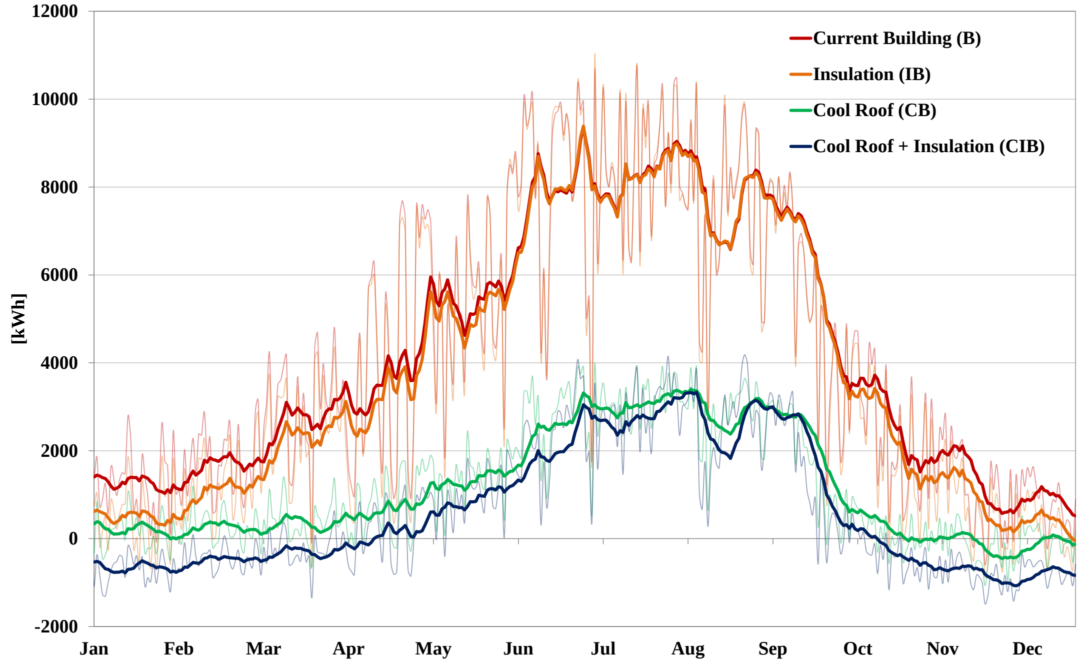

Figure 8. Heat released by the whole building. Daily average (transparent lines) and 15 days moving average trendlines (thick lines).

Figure 9 shows the external roof surface temperature profiles simulated for three typical summer days of August and demonstrates that, by adding the insulation layer, the temperature values do not significantly decrease compared to Case B (average and peak daily decrease respectively of 0.4 °C and 1.3 °C). On the other hand, the external surface temperature profile during day time notably decreases by the application of cool roof (average and peak daily decrease respectively of 10.4 °C and 20.5 °C), thus reducing the risks for the durability of the waterproofing external membranes.

As can be seen in Figure 9, during night time the external surface temperature is lower than the ambient temperature, thus the heat flux assumes negative values. The result is consistent with other studies which can be found in literature [15] and it is mainly caused by the high emissivity of roof finishing materials.

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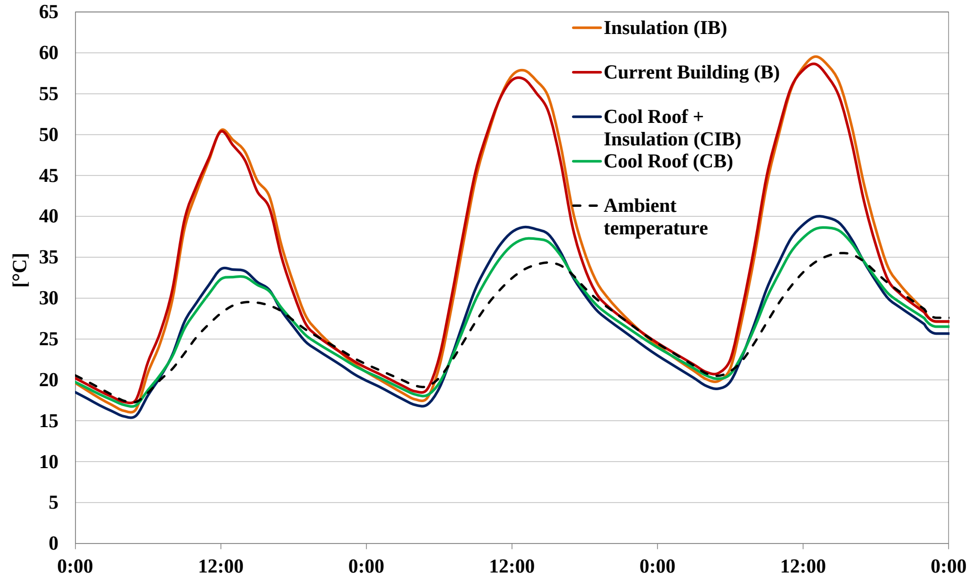

Figure 9. Average ambient and external roof temperature profiles simulated for three summer days.

Figure 10 represents the heat released by the whole building to the environment during a typical summer day of August. The daily energy profile shows that the energy released by the building more than halves when cool coated surfaces are considered (Case CB), while the energy values for the insulated building (Case IB) do not change significantly (average increase of 1%). When cool coated surfaces and insulating layers are considered (Case CIB), the energy released by building decreases by about 60%. During night time, with the AC system switched off, since the outer surface temperatures are lower than the external air temperature (see Figure 9), the building envelope lightly absorbs heat from the surrounding environment. It is also possible to observe that the higher level of insulation leads to a slightly increased energy need for the air-conditioning system. This result is mainly due to the rather significant amount of internal gains, especially related to occupancy, that are less efficiently released through the more insulated envelope.

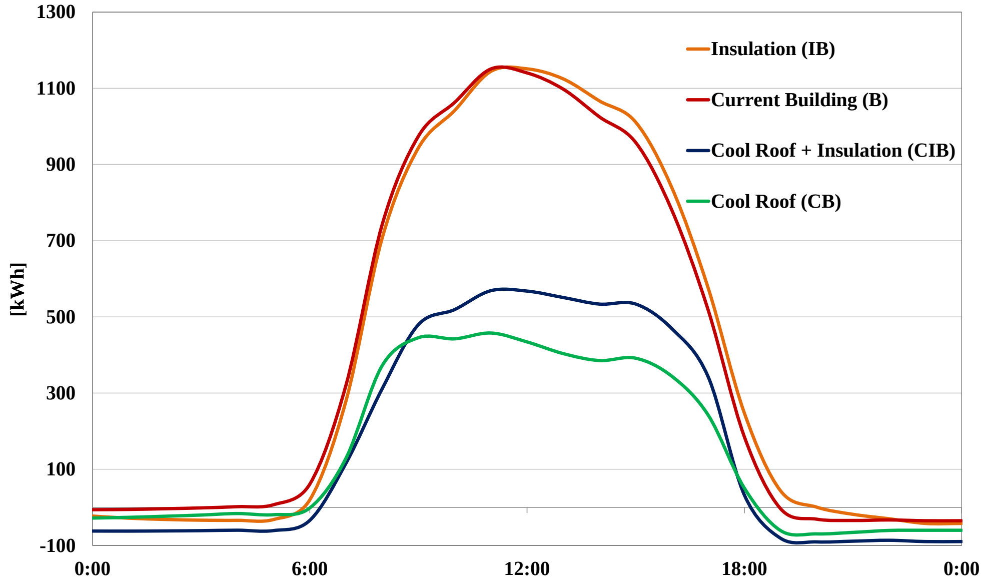

Figure 10. Heat released by the whole building during a typical summer day.

In Figure 11 a comparison between the 15-day moving average trendlines of the heat released by building envelope, excluding the longwave radiation to high atmosphere, and the

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heat released due to HVAC system is outlined for Case B, CB and CI. The graph points out that the heat released due to HVAC system during the heating season presents very similar trends for Case B and CB. A reduction for the highly insulated building model is noticed. The 15-day moving average trends confirm that during winter period the application of cool materials is not affecting significantly the heat released due to the heating system.

Moreover, Figure 11 underlines that during the summer period the heat released by the building envelope to the near ground atmosphere is much more relevant than the heat released by the cooling system, as it is found in Figure 4.

During winter period, for Case CIB, with cool roof combined with a highly insulated envelope, the heat absorption by building envelope is higher than heat released due to AC system, observing a further decrease of UHI effect. The phenomenon is due to the lower external surface temperatures consequent to the application of the insulating layer.

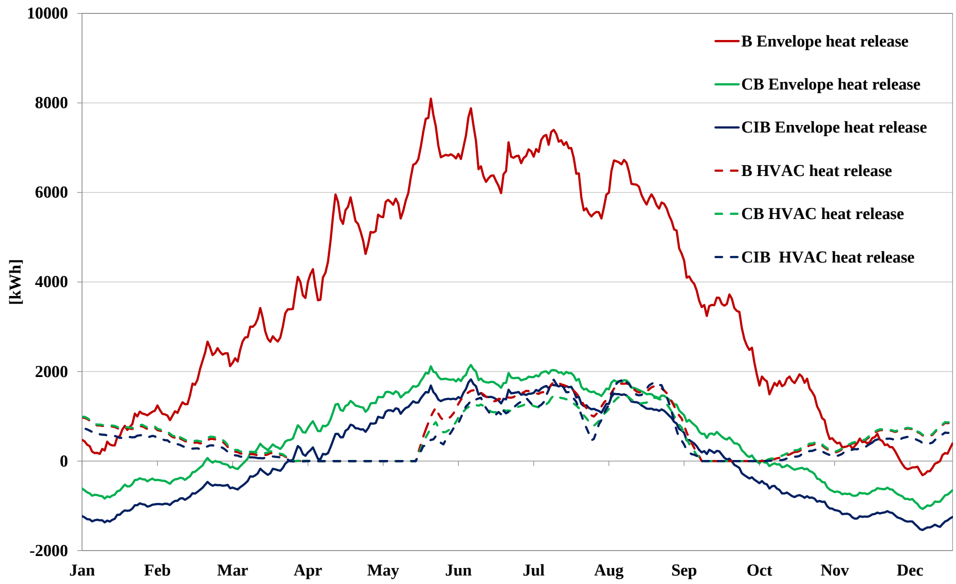

Figure 11. Heat released by the building envelope and the HVAC system for the following cases: Current Building (B), Cool Roof (CB) and Cool roof + Insulating layer (CIB). 15-day moving average trendlines.

Conclusions

This study quantified the contribution on UHI effect presented by a typical tertiary building during the whole-year period. In particular the study considered the heat release to the ground level atmosphere by the building envelope and the HVAC system as the whole building contribution on UHI effect. The results have been obtained by dynamic simulation of thermal behavior of the building, with internal loads and an HVAC system.

Regarding the heat released by the building envelope, the study demonstrates that it is important to exclude longwave radiation to the sky in the assessment of the contribution to the UHI. In fact, this contribution is not negligible in comparison to the energy released by the envelope to the surrounding atmosphere at ground level.

Besides, the heat released by the HVAC system has been considered with a comprehensive approach. During the summer period the heat released by the air conditioning system is assumed to be the heat extracted from the building envelope and the energy consumption of the AC system. On the other hand, during the winter period it corresponds to the heating system energy losses, excluding a portion of recovered distribution losses.

The study demonstrates that during the summer period the heat released by surfaces is much more relevant than the energy released by the HVAC system. Moreover, the heat released by several kinds of external building envelopes has been evaluated. The results presented in this study show the effectiveness of the application of cool materials on external

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surfaces in reducing the effect of UHI. On the other hand, the presence of an insulating layer in the building envelope does not yield a significant reduction of the heat released especially during the summer period.

Regarding the effects on external roof surface temperature, cool coatings application carries out an average and a peak daily decrease respectively of about 10°C and 20°C, improving the durability of the waterproofing external membranes. On the contrary, by adding the insulation layer the temperature values do not significantly decrease.

During the winter period the application of cool materials does not seem to affect significantly the heat released to the near ground atmosphere, especially in comparison with the advantages in the summer period.

The contribution to the formation of UHI represented by other types of buildings, residential and non-residential ones, will be analyzed and compared in the next future.

Nomenclature

Variables

c	Specific heat capacity	[kJ/(kg K)]
g	Solar factor	[-]
s	Thickness	[m]
U	Thermal transmittance	[W/(m^2 K)]
α_{sol}	Solar absorptance	[-]
λ	Thermal conductivity	[W/(m K)]
ρ	Density	[kg/m^3]

Subscripts

g	Transparent vertical surfaces
r	Opaque horizontal surfaces (roof)
w	Opaque vertical surfaces (walls)

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