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Article

Experimental Analysis of Cool Traditional Solar Shading Systems for Residential Buildings

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Abstract: In recent years there has been a growing interest in the development and thermal-energy analysis of passive solutions for reducing building cooling needs and thus improving indoor thermal comfort conditions. In this view, several studies were carried out about cool roofs and cool coatings, producing acknowledged mitigation effects on urban heat island phenomenon. The purpose of this work is to investigate the thermal-energy performance of cool louvers of shutters, usually installed in residential buildings, compared to dark color traditional shading systems. To this aim, two full-scale prototype buildings were continuously monitored under summer conditions and the role of the cool shutter in reducing the overheating of the shading system and the energy requirements for cooling was analyzed. After an in-lab optical analysis of the cool coating, showing a huge solar reflectance increase with respect to the traditional configuration, *i.e.*, by about 75%, field monitoring results showed that the cool shutter is able to decrease the indoor air temperature up to 2 °C under free floating conditions. The corresponding energy saving was about 25%, with even much higher peaks during very hot summer conditions.

Keywords: cool coatings; reflective shading systems; building continuous monitoring; residential building; thermal performance; passive cooling; test-room; indoor microclimate; energy efficiency in buildings

1. Introduction

The reduction of building energy requirements for cooling is becoming an increasing environmental issue to be addressed since an energy peak is registered in summer hot days, even in temperate countries such as Italy [1]. While the national regulation has been largely developed around decreasing thermal losses through the envelope, and optimizing the winter energy performance of buildings, a few suggestions were mentioned for saving energy in summer and improving indoor environmental quality [2,3]. In particular, passive cooling techniques, such as cool roofs and green roofs, are assuming increasing importance in the scientific community, interested in developing cost-optimal and sustainable techniques for this purpose [4,5]. In this respect, cool roofs and cool coatings in general represent passive solutions aimed at reducing solar gain entering building roofs and facades by means of the installation of highly solar reflective surfaces, e.g., tiles or paint coatings or shells [6–8]. Such systems are of interest to the scientific community for three reasons: they have been demonstrated to reduce energy requirements for cooling and to improve indoor thermal comfort under summer conditions [9,10] and additionally, their capability to reflect solar radiation can mitigate urban heat island and global warming phenomena [11,12].

In this respect, several researchers have studied the effect of cool coatings in roof applications with varying building characteristics, end use, and climate boundary conditions. In particular, a recent research by Mastrapostoli *et al.* [13] showed an important energy saving for cooling of up to 73% with a corresponding winter penalty of 5% in Northern-Europe cold climate conditions. In this experiment, a case study industrial building in The Netherlands was selected and the horizontal roof was painted by mean of an innovative high albedo cool coating. Several studies were carried out in school and university buildings in Europe, also thanks to important international cooperation initiatives such as the Cool Roof project [14]. In fact, Synnefa *et al.* studied in [15] the effect of cool roofs when applied to a school building in Athens by means of experimental analysis and calibrated numerical simulation developed in order to extend the results of the experimental campaign to year-round assessment. They showed that the cool roof was able to reduce the cooling energy requirements by up to 40% and the indoor air temperature in the classrooms by up to 2.8 °C. Important and consistent results were also achieved by the Heat Island Group in the US, where local policies encouraged the use of such systems in buildings and urban areas [16–18].

As previously showed, while cool roofs have been widely investigated by mean of experimental and numerical studies [19], cool facades are still rarely studied and only a few contributions deal with the experimental analysis of cool coatings or naturally cool stones applied over façade systems in buildings [14,20]. In particular, researchers have recently focused on the role of façade albedo on energy demand and thermal comfort by mean of dynamic simulations [21,22]. Additionally, Zinzi *et al.* [23] studied the effect of cool coatings applied over window shading systems demonstrating how this solution could produce non-negligible benefits in summer, reducing the solar gain entering the window. Also in this study, after an in-lab experimental characterization of solar reflectance of the tested cool coating, commercial dynamic simulation software was used to analyze this phenomenon.

By considering previous contributions concerning the role of shading systems on building energy efficiency, very notable research was carried out by means of experimental and numerical tools. In particular, innovative and reliable simulation tools were investigated in [24]. The integration of photovoltaic systems in shading technologies was also studied in [24]. Combined window and shading optimization strategies were also assessed in [25], where several solutions were compared by mean of dynamic simulation software using a reference room of a residential building.

In this scenario, very little research has shown the effect of shading systems by mean of experimental analysis, which is very much required in this field, given the wide variability of the solar force and its effects on building thermal-energy performance. Some recent contributions were focused on different types of shutters (louvers) with the purpose of studying their environmental impact and their role in affecting building energy performance and indoor thermal comfort conditions [26]. Hashemi in [27] carefully analyzed the effect of internal reflective louvres for office buildings with a focus on the role of such shading systems on daylighting. However, no focus on the role of louvers' solar reflectance from a thermal point of view was previously investigated experimentally by means of long-term continuous monitoring campaign, which is the purpose of the work presented in this paper. Therefore, this study builds upon previous key research about cool coatings, cool roof applications and window shading systems in order to experimentally evaluate the effect of a cool shutter system in reducing building cooling energy requirements and improving indoor thermal comfort conditions. In fact, the research in this field still lacks any experimental continuous monitoring campaigns demonstrating and quantifying the effectiveness of cool shutter systems with varying weather conditions and building operation, which is the purpose of this work. To this end, in order to characterize the optical properties of the shutter, spectrophotometric analyses were carried out on both traditional dark and cool shutter coatings. Therefore, a parallel continuous monitoring was set up in a dedicated pair of full scale buildings (test-rooms) representing typical Italian residential construction in terms of materials and window surface with respect to the surface area of the thermal zone. Finally, a detailed field analysis of: (i) the energy requirements for cooling; (ii) the thermal behavior of the shading system and (iii) of the indoors is carried out, as original contribution of the work, under both free floating and controlled temperature operations.

2. Materials and Methods

The thermal-energy analysis of the cool shutter system was performed by means of coupled in-lab and in-field experimental measurements characterizing the baseline scenario, *i.e.*, before the application of the cool coating, and the optimized scenario. The experimental field used in this research consists of two continuously monitored full-scale prototype buildings representing Italian construction typical of residential buildings. The main phases of this experimental work are reported as follows.

2.1. In Lab Experimental Characterization

The surface optical analysis of the shutter systems was carried out by mean of a solar spectrophotometer and thermal portable emissometer, used to measure solar reflectance and thermal emittance, respectively, of the Baseline Scenario (BS) and of the "Cool" Configuration (CC). In particular, a Shimadzu SolidSpec 3700 (Shimadzu Corporation, Kyoto, Japan) was used to measure the solar reflectance profile in the 240 ÷ 2,600 nm spectrum interval, with a 0.1 nm resolution level and a wavelength accuracy of ±0.2 nm and ±0.8 nm in the ultraviolet/visible and near infrared region, respectively. The procedure was developed according to [28] and the solar reflectance calculations were carried out by taking into account the reference solar spectrum reported in [29]. Thermal emittance measurements were performed by mean of portable emissometer, according to [30].

2.2. In Field Continuous Monitoring Campaign

As previously mentioned, two geometrically equivalent dedicated buildings were used for comparing the thermal-energy performance of the cool shutter with respect to the traditional dark shutter. For this purpose, a continuous monitoring campaign was designed in order to measure the thermal effect of the optimized shutter on external surface shutter temperature ($T_{e\text{-}s}$), internal surface shutter temperature ($T_{i\text{-}s}$), air-gap temperature between the shutter and the glass system (T_{ag}), indoor air-operative-mean radiant temperature (T_{air}, T_{op}, T_{mr}). All these parameters were compared to significant weather variables such as outdoor dry bulb temperature (T_{out}) and global solar radiation on a horizontal plan (G_h) measured on the roof of a building located in close proximity. The permanent continuous monitoring setup (Figure 1) allowed a measurement every 20 s and post-processing of all the microclimate and weather data [31], while the specific sensors applied on the shutter systems, measuring $T_{e\text{-}s}$, $T_{i\text{-}s}$, and T_{ag}, consisted of independent temperature probes with incorporated data-loggers dedicated to this campaign. In particular, these sensors were (i) Tinytag Plus 2 (−40 to +85 °C) TGP-4017 with a 10K NTC internally mounted thermistor (Gemini Data Loggers Ltd., Chichester, UK) for measuring T_{ag}; and (ii) Tinytag Plus 2 with a 10K NTC surface thermistor sensor type measuring superficial temperatures $T_{es\text{-}s}$, $T_{is\text{-}s}$ in a range (−40 to +125 °C), with an accuracy of 0.2 °C in (0 to 70 °C) thermal range [32].

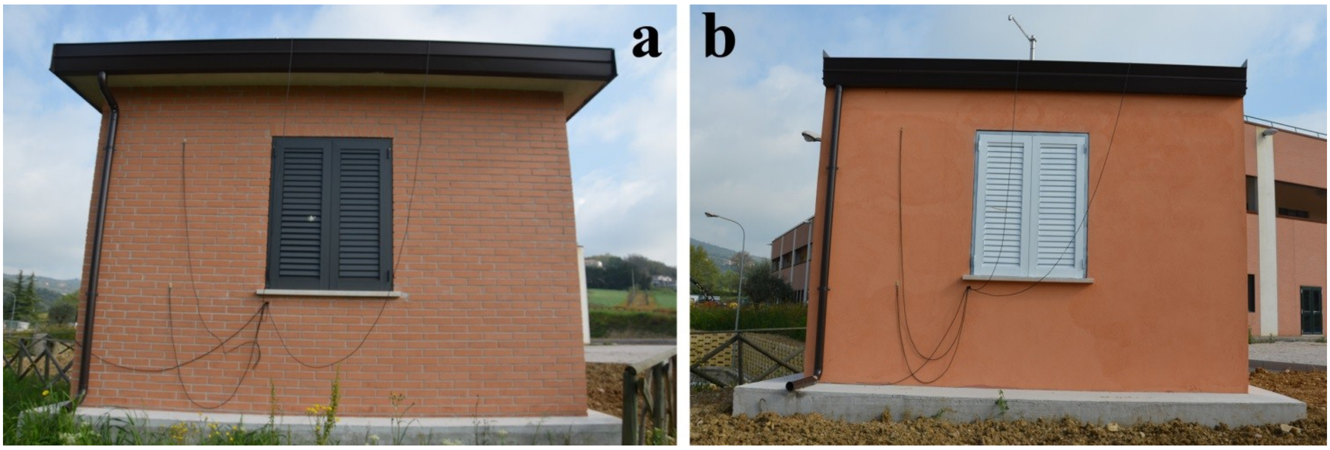

Figure 1. Continuously monitored buildings. (**a**) Test-room 1 with the Dark Shading system; (**b**) Test-room 2 with the Dark Shading system.

The agenda of the continuous monitoring campaign was designed in order to analyze a Baseline Scenario (BS) conditions, *i.e.*, before the application of the cool coating over one shutter, and the optimized Cool Scenario (CS) with varying weather conditions and indoor operative setups of the HVAC (Heating, Ventilating and Air Conditioning) systems. In particular, the step-by-step layout of the campaign is reported in Table 1. Therefore, the continuous monitoring allowed assessing the thermal-energy effect of the cool shutter in free floating and thermally controlled regimes.

The thermal properties of the two test buildings are reported in Table 2, where thermal properties of opaque envelope components of the test-rooms were calculated according to [33].

Table 1. Agenda of the continuous monitoring campaign.

Period	Event	Shutter Configuration	HVAC Conditions	Weather Conditions
10 February 2014	Installation of independent sensors	Traditional baseline scenario (BS) with dark shutters	HVAC switched ON *	Cold winter
18 February–10 April 2014	Continuous monitoring	BS scenario	HVAC ON *	Cold–mild winter
10–12 April 2014	Application of the cool coating over one shutter	Test-room 1 with dark traditional shutter and Test-room 2 with cool colored shutter (CC scenario)	HVAC ON *	Mild winter
12 April–12 June 2014	Continuous monitoring	CC scenario	HVAC ON *	Spring–early mild summer
12 June 2014	HVAC switching OFF	CC scenario	HVAC OFF	Spring–early mild summer
12 June–27 August 2014	Continuous monitoring	CC scenario	HVAC OFF	Summer
27 August 2014	HVAC switching ON	CC scenario	HVAC ON*	Summer
27 August–30 September 2014	Continuous monitoring	CC scenario	HVAC ON	Summer

* setup T_{air} = 20 °C in both the test-rooms.

Table 2. Thermal characteristics of test-rooms' envelope.

Test-room	Envelope System	Stationary Thermal Properties	Insulation Characteristics
Test-room 1	Opaque wall	Thermal transmittance: 0.28 W/m^2·K Internal heat capacity: 128.8 kJ/m^2·K	Brickwork, outer leaf: 0.12 m Plasterboard: 0.01 m EPS insulation: 0.09 m Brickwork, inner leaf: 0.25 m Gypsum plastering: 0.02 m
	Roof	Thermal transmittance: 0.24 W/m^2·K Internal heat capacity: 50.7 kJ/m^2·K	Clay tile: 0.015 m Mineral wool insulation: 0.015 m Air gap: 0.05 m Mineral wool insulation: 0.08 m Aerated concrete slab: 0.20 m Gypsum plastering: 0.015 m
Test-room 2	Opaque wall	Thermal ransmittance: 0.28 W/m^2·K Internal heat capacity: 128.8 kJ/m^2·K	Bitumen sheet: 0.01 m Mineral wool insulation: 0.10 m Aerated concrete slab: 0.20 m Gypsum plastering: 0.015 m
	Roof	Thermal transmittance: 0.24 W/m^2·K Internal heat capacity: 50.7 kJ/m^2·K	Plaster dense: 0.02 m EPS insulation: 0.09 m Brickwork, inner leaf: 0.30 m Gypsum plastering: 0.02 m
Both the test-rooms	Ground floor	Transmittance: 0.30 W/m^2·K Internal heat capacity: 200 kJ/m^2·K	Linoleum: 0.004 m Glass fiber slab: 0.10 m Cast concrete: 0.30 m
Both the test-rooms	Glazing systems	Solar heat gain coefficient g (%): 42 Thermal transmittance U (W/m^2·K): 1.3	

2.2.1. Analysis of the Baseline Scenario (BS)

In order to compare the thermal performance of the window system and the indoor environment of the two test-rooms with varying the shutter reflectance, the configuration of the test-room buildings before the implementation of the cool shutter was analyzed and indicated as Baseline Scenario (BS). In particular, the thermal behavior of the shutter system and the indoor thermal behavior of the buildings were compared in order to identify their performance before the modification of solar reflectance capability in only one test-room (TR-2, Figure 1b). Therefore, all the considerations carried out to compare the two scenarios (BS and CS), were performed by taking into account the comparative dynamics of the two monitored buildings, before the optimization of the shutter.

2.2.2. Analysis of the Cool Scenario (CS)

The analysis of the cool shutter was performed starting from the results of the BS aimed at defining a sort of reference behavior of the test-rooms. After the implementation of the cool shutter, a comparative analysis of the CS applied in TR-2 compared to the non-cool scenario in TR-1 was carried out, by considering both free-floating and indoor thermal controlled conditions. In particular, external and internal surface temperature of the shutters and the air temperature measured between the shutter and the glass (T_{ag}) were registered every 10 min for both the test-rooms in parallel. A comparative assessment has been performed in order to investigate the overheating reduction of the window system and its effect on the indoors. The CS was also analyzed in terms of energy requirements for cooling, indoor air and mean radiant temperature in the center of the thermal zone, by comparing the cool shutter TR-2 with respect to the non-cool shutter installed in TR-1.

3. Discussion of the Results

3.1. Analysis of the Optical Properties

The lab measurements (Figure 2) indicate a huge increase of solar reflectance of the Cool Shading system, which reported to have a solar reflectance of 84.67% *vs.* 7.98% of the Dark Shading system. The thermal emittance of both systems was measured and gave the same value, *i.e.*, 0.86 [30].

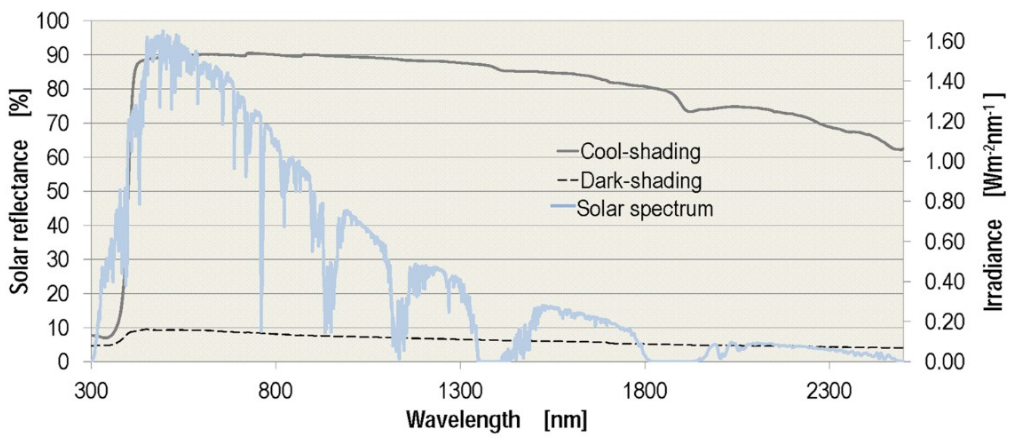

Figure 2. Spectrophotometer measurement results of solar reflectance of Cool Shading *vs.* Dark Shading.

3.2. Analysis of the Baseline Scenario

The baseline analysis was carried out in order to monitor and to study the thermal-energy behavior of the continuously monitored prototype buildings before the implementation of the Cool Shading system in one of the buildings (TR2–Test-Room 2, Figure 1b). Figure 3 reports the thermal profiles of the air-gap temperature and internal surface temperature of the shading systems in both the test-rooms. It shows how the two buildings could be approximated to have equivalent thermal behavior for the purpose of this work, since the average difference during the monitoring period (10 February–10 April) was 0.2 °C in terms of air gap temperature. The differences between thermal maximum and minimum peaks were 0.14 °C and 0.064 °C, respectively. Therefore, the following analysis of the shading system will take into account these few differences. The all data of the monitored period are reported in Figure 4, where a negligible difference was confirmed between the two test-rooms.

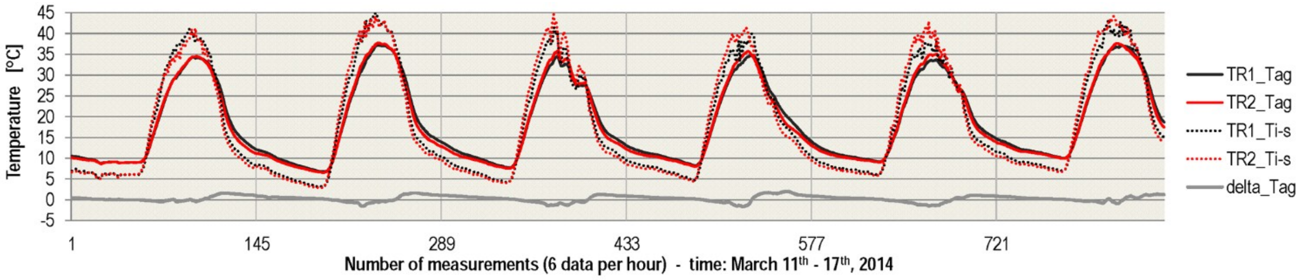

Figure 3. Thermal profiles of the monitored test-rooms during the baseline characterization.

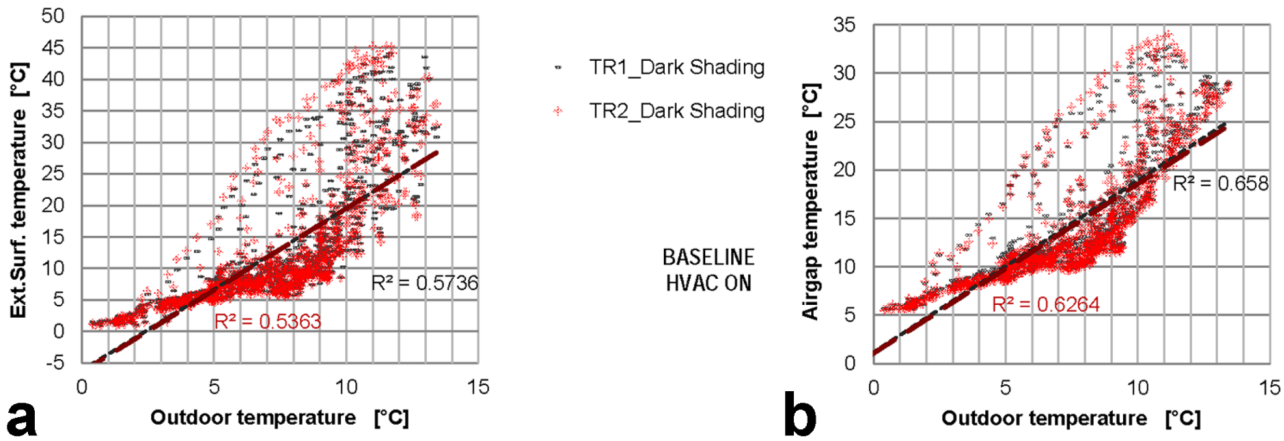

Figure 4. Shutter external surface temperature (**a**) and airgap temperature (**b**) of the two test-rooms *vs.* outdoor thermal conditions in baseline configuration.

Figure 5 reports the main indoor thermal parameters affecting indoor thermal comfort conditions in buildings: air temperature of each test-room (a) and mean radiant temperature (b). These thermal parameters showed a non-negligible difference between the two buildings, which have been taken into account in further analyses. While the average difference in terms of air temperature was lower than 0.4 °C, the mean radiant temperature registered different values in cold outdoor conditions (up to about 0.7 °C). In particular, TR-2 was colder than TR-1 in terms of both T_{air} and T_{mr}. This finding guided the choice of the test-room where the Cool-Shading should be installed. In fact, the Cool-Shading has been installed in the hotter test-room (TR-2) in order to making safe the results of this experiment, and to underestimate the effect of the cool shutter. These peculiarities could be motivated by the fact that the test-rooms were designed in order to have the same stationary properties (Table 2) but they are characterized by different dynamically variable properties, such as roof solar reflectance, for instance. These properties mainly affect the surface temperature of the opaque envelope systems, detected by mean of global thermometer measuring mean radiant temperature within each test-room.

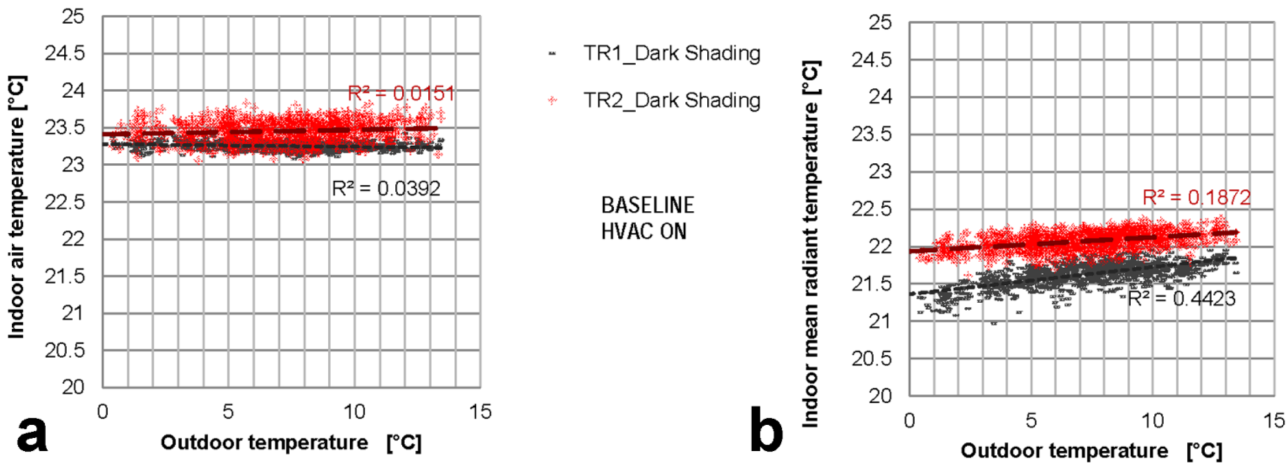

Figure 5. Indoor thermal behavior of the test-rooms before the implementation of the Cool Shading systems in TR2. Indoor air temperature trends (**a**), and mean radiant temperature trends (**b**).

3.3. Thermal Behavior of the Shading System

The analysis of the thermal behavior of the monitored shading system was carried out in order to highlight its effect in terms of passive cooling for the prototype buildings. In particular, Figure 6 shows four typical monitored summer days where the air-gap temperature of the CS scenario was lower than the DS by about 7 to 9 °C. The external surface temperature registered, as expected, even bigger differences, by about 17–20 °C. Important results were also found in terms of internal surface temperature, which difference was about 15 °C on sunny summer days. Consistent trends were shown in late springtime, when the CS effect was weaker than in summer, but still very important, since the difference in terms of air gap temperature was about 6–8 °C.

Now the air and surface temperature of the shading system is analyzed *vs.* outdoor parameters such as global solar radiation and outdoor dry bulb temperature, monitored by mean of the same experimental apparatus (Figure 7). The main data collected in summer (12 June–27 August) in free floating conditions showed that there was an important correlation between external thermal conditions and the thermal behavior of shading air gap, while this correlation was weaker with respect to the radiative conditions of the site. Nevertheless, the Cool-Shading was shown to play a key role in cooling surface and the air gap adjacent to the glass camera of the building under hot and sunny conditions, by producing an air gap temperature decrease up to 6 °C during daily hot peaks, *i.e.*, when most required. The external surface temperature decreased by 12 °C at radiation peak time, that was shown to have a dominant effect in affecting the surface temperature of the shutter, with respect to the outdoor dry bulb temperature.

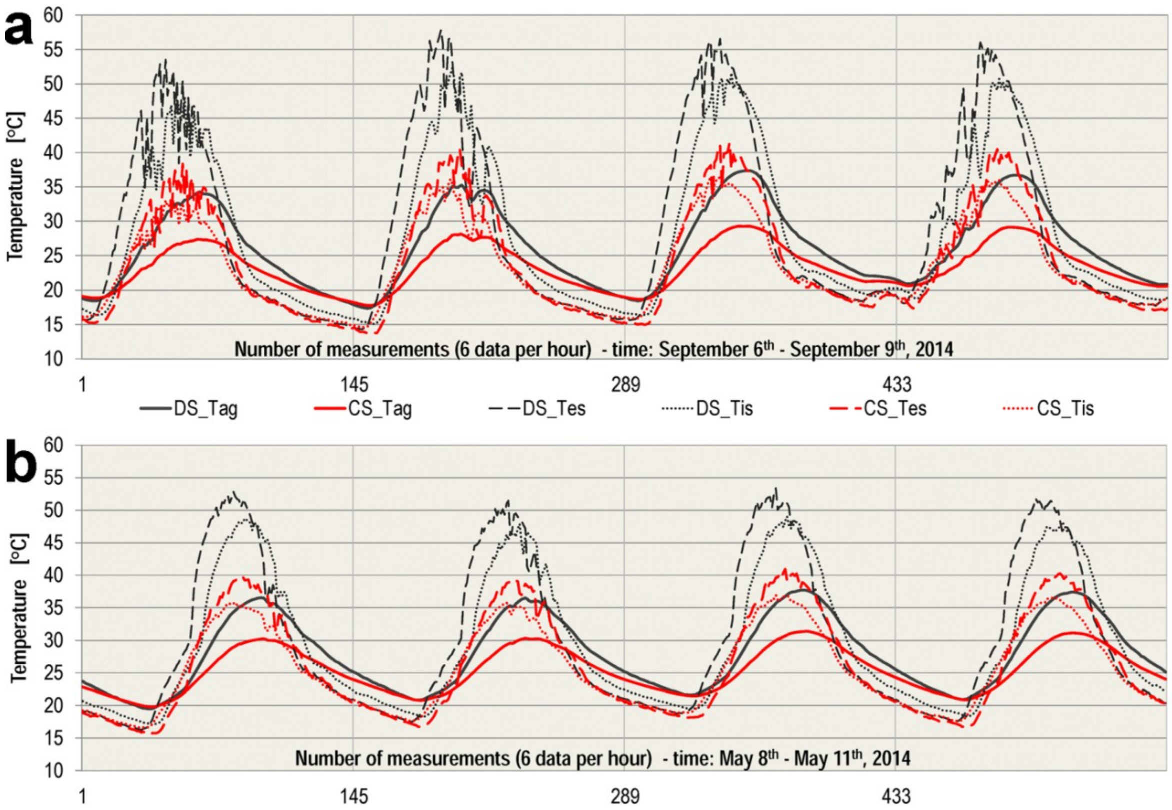

Figure 6. Indoor thermal behavior of the test-rooms before the implementation of the Cool Shading systems in TR2. (**a**) Summer conditions; (**b**) Spring conditions.

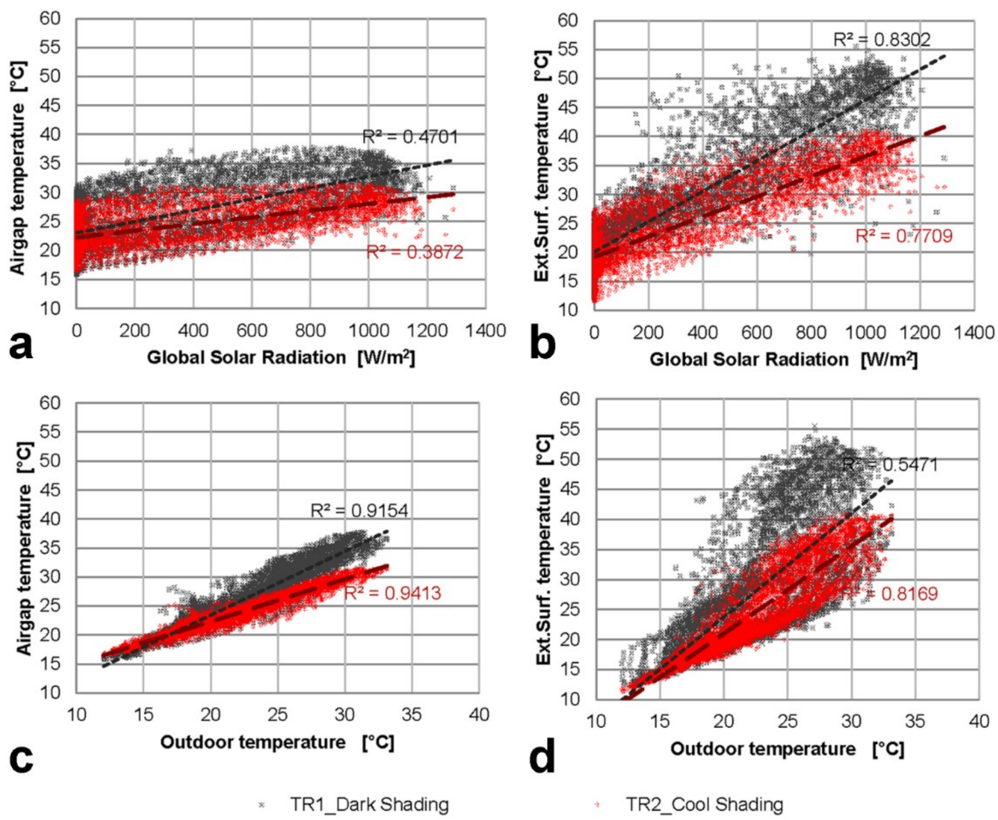

Figure 7. Air gap and surface temperature of the shutters *vs.* outdoor weather parameters. (**a**,**b**) Global solar radiation over an horizontal plane; (**c**,**d**) Outdoor dry bulb temperature.

3.4. Thermal Behavior of the Indoors

The indoor thermal comparative analysis is carried out by considering both the free floating conditions and the operative-HVAC conditions. Figure 8 shows the indoor mean radiant temperature and air temperature values *vs.* the outdoor temperature trends when the cooling system was operating. Despite the HVAC system operation effect on the air temperature, there were non-negligible differences between CS and DS, *i.e.*, up to 1.2–1.5 °C, registered in hot weather conditions. Even larger effects were found in terms of mean radiant temperature, as expected. Additionally, these differences were in the opposite direction with respect to the baseline analysis where the TR-2 (Cool Shading scenario) was the hottest one. Therefore, the effects of the installed cool shutter have to be considered even larger than the ones plotted in Figure 8, by taking into account the observations reported in Section 3.2 of this work.

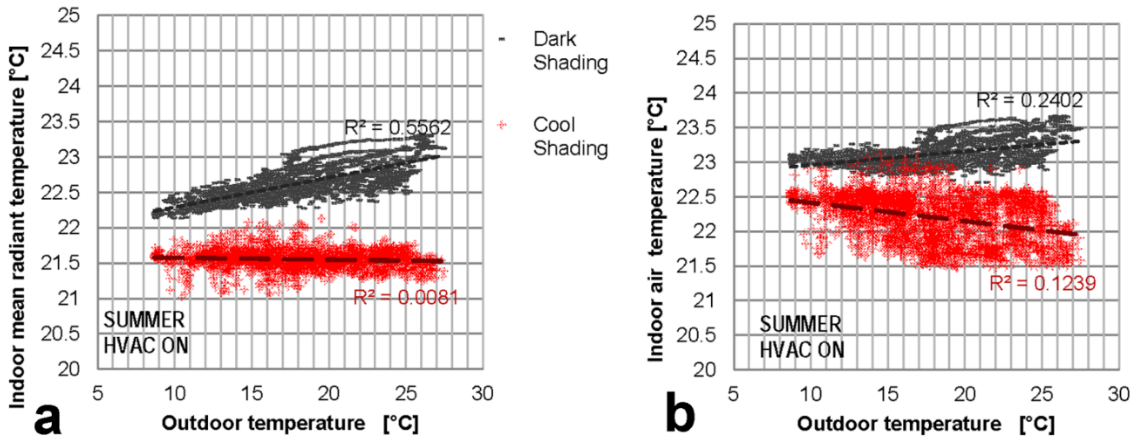

Figure 8. Indoor thermal comparative assessment of the two configurations in terms of (**a**) mean radiant temperature and (**b**) air temperature, when the HVAC system is operative.

The comparative thermal analysis of the two scenarios is then performed in free floating conditions, in summer period (12 June–27 August). The results (Figure 9) showed that the monitored data are more dispersed but the overall effect of the Cool-Shading system is very important, being able to decrease indoor air and mean radiant temperature up to 2 °C in hot weather conditions.

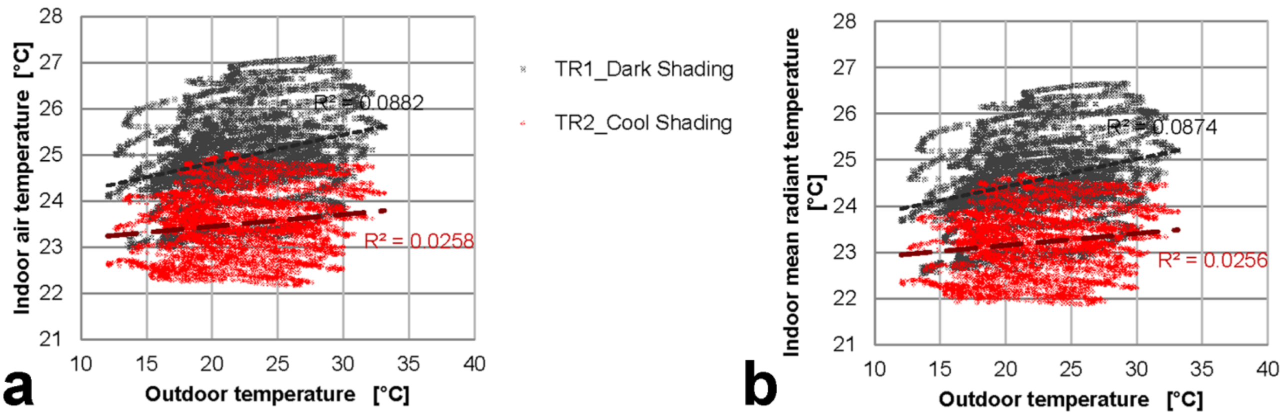

Figure 9. Indoor thermal comparative assessment of the two configurations in terms of (**a**) air temperature and (**b**) mean radiant temperature, in free floating conditions.

3.5. Energy Analysis

The analysis of the energy performance of the prototype buildings showed that the Cool Shutter produced an important reduction in the cooling energy requirements as reported in Figure 10. The graph shows the daily cumulative energy requirements of TR-2 and TR-1, in CS and DS configuration, respectively. CS registered much lower energy needs than DS with varying weather conditions, as described by the two lines representing the daily maximum peaks of global solar radiation and outdoor dry bulb temperature. In particular, the correlation coefficient between the energy saving (varying from 12.6% and 54.2%) and the outdoor thermal peak was calculated and the Pearson coefficient was about 90%, while the Pearson coefficient calculated between daily energy saving and solar radiation peak was –25%. Therefore, the main experimental findings demonstrated how the more is the outdoor thermal peak, the more is the shutter effect in reducing cooling energy consumption, with no evident correlation with daily global solar radiation peaks.

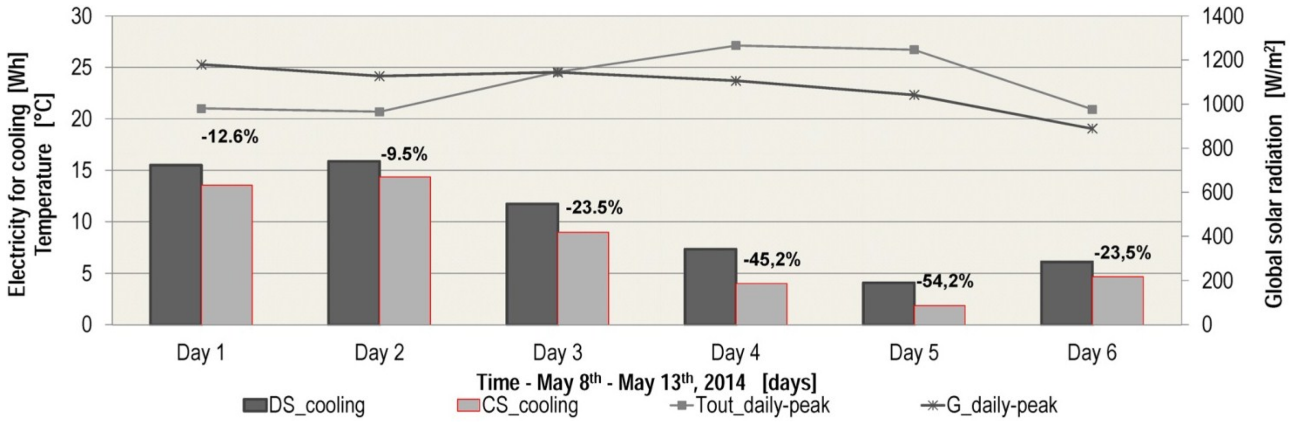

Figure 10. Daily energy requirement for cooling of CS and DS with varying daily weather parameters, *i.e.*, outdoor dry bulb temperature and global solar radiation.

4. Conclusions

Starting from previous studies about the effect of cool roof systems and cool coatings for reducing building energy consumption in summer, this study aimed at experimentally assessing the in-field behavior of cool shutters *vs.* traditional dark coated shutters. To this end, a dedicated continuously monitored experimental apparatus was used in order to monitor these two shading systems in parallel, with varying weather conditions and operative conditions, *i.e.*, free-running and controlled thermal setup. The experimental apparatus consisted of two full-scale prototype buildings representing typical residential construction where two microclimate stations and one weather outdoor station are installed and used for the purpose of the work. Additionally, this permanent system was integrated with a dedicated monitoring system of the shutters and the air-gap between the shutter and the glass camera of the window positioned within the South-facing façade of the building. A preliminary experimental analysis of the coating was operated. Solar reflectance and thermal emittance was measured. The Cool Scenario shutter showed a higher solar reflectance than the Dark Scenario by about 76%. This difference produced a passive cooling effect of the air gap by up to 6–8 °C in hot peak conditions. Also the indoors were cooled by the passive system, showing a lower temperature by about 1.5 °C and

2 °C in controlled and free-running conditions, respectively. The energy analysis showed that the cool shutter was able to largely reduce the energy requirement for cooling of the Cool Scenario, in hotter days in particular. This experimental analysis finally showed how the cool shading system could represent an effective and sustainable retrofit intervention in residential buildings, even where cool roofs are not likely to be applicable for technical or/and economic reasons.

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Conflicts of Interest

The author declares no conflict of interest.

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