COOL ROOF FOR PASSIVE COOLING: SIMULATIONS OF AN EXISTING BUILDING IN SOUTHERN ITALY

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ABSTRACT

Roofs are the envelope component more severely hit by solar radiation in summer (1470 kWh/m^2 on average in Italy), hence one may expect that using *cool materials* on the finishing layer of a roof should provide a significant reduction in the heat flow entering the building, with sensible relief in terms of building cooling load.
In this paper a case study is presented, based on the dynamic simulation of an existing office building in Catania (Southern Italy). In this building, a part of the roof has been recently treated with a commercial cool painting, with the aim of improving the thermal comfort in summer. Hence, the simulations represent a preliminary study, that will allow to assess the expected effectiveness of the intervention. More in detail, the results of the simulations will be discussed both in terms of thermal comfort and energy savings due to the use of the cool painting, through the evaluation of parameters such as the roof surface temperature, the operative temperature and the cooling load for both conditions, i.e with and without the cool painting on the roof.
The paper also discusses the potential increase of the energy needs for winter heating, and looks at the overall balance in terms of primary energy. These aspects are usually not well highlighted in the current scientific literature.

KEYWORDS

Cool Roof case study, occupants' comfort, building energy performances, design suggestions

1 INTRODUCTION

The roof surface represents about 20-25% of urban surfaces and 60-70% of the building envelope on average in Italy, depending on the building typology (Corrado, 2011); thus, it plays a very important role in the energy balance of buildings, and it is important to find appropriate solutions to improve its energy performance, also in relation to the specific climate.
In this context, *cool materials* represent an efficient way to cope with the increase of energy consumption in summer and the urban heat island effect, without a sensible change in the aesthetic feature (Synnefa, 2007). As an example, Levinson (Levinson, 2007) have developed some materials (mainly paintings) whose chromatic result is as close as possible to the existing original color of the untreated roof, showing how this is obtainable by maximizing the near infrared reflectance without affecting the behavior of the painting in the visible field, which is strictly related to the perceived color.
Cool materials are characterized by high values of solar reflectance ($r > 0.6$), which strongly reduces the amount of solar radiation absorbed by the roof outer layer, and by high infrared emissivity values ($\varepsilon > 0.8$), which contributes to dissipate the heat accumulated during the day through an intensive radiant heat exchange at night.

In order to discuss the suitability of the cool roof technology as a passive cooling strategy for hot climates, this paper presents the results of a case study in Catania (southern Italy), based on simulations with the software tool EnergyPlus.

The simulations will allow to evaluate the results to be expected from the application of a commercial cool painting on a low-rise office building; this intervention has already been performed, and it will be the object of an experimental monitoring campaign.

The results of the simulations will show the benefits of using cool roofs on existing buildings, both in terms of reduction of cooling demand and decrease of the hours of thermal discomfort. However, attention will be also paid to the winter condition, when the presence of the cool painting lowers the heat absorbed by the roof, with consequences in terms of heating demand. Actually, this is a drawback of cool materials not always addressed in the scientific literature.

2 METHODOLOGY

The study has been developed in two different phases: the first stage involved the characterization of the building envelope in terms of thermal and optical properties, whereas in the second stage the calculation of the energy performance and the study of the thermal comfort were carried out through a series of dynamic simulations.

2.1 Characterization of the building envelope

The evaluation of the thermal transmittance (*U-value*) of the opaque envelope components was supported by a measurement campaign of the envelope transmittance values, carried out through a Heat Flux Meter; the instrument chosen to this purpose is the TESTO 435-2 multifunction instrument.

On the other hand, before applying the product to the roof, laboratory tests were conducted to characterize its spectral reflectance. To this aim the Perkin Elmer Lambda 750 UV/Vis/NIR spectrophotometer was used, according to ASTM E 903-96 standard (ASTM, 1996).

In this way the global reflectance value r was calculated, while the same value for the untreated roof has been deduced from Levinson (Levinson, 2010) and Romeo's (Romeo, 2011) studies.

Both the *U-value* of the envelope components and the r value of the existing clay tiles and of the cool painting are summarized in Table 1.

2.2 Assessment of the thermal and energy performance of the building

The assessment of the energy performance and the thermal comfort conditions in the sample building are carried out using the software for dynamic thermal analysis EnergyPlus v.7.0.

In order to carry out a thermal comfort analysis of the building, the operative temperature has been chosen as an index closely related to the comfort condition perceived by the occupants, so a reduction of its value during the period of observation implies better conditions for the building occupants.

An effective way to quantify the intensity of uncomfortable thermal sensation due to overheating in a living space is the measure of the difference between the room operative temperature and a threshold value; however, the duration of such overheating should also be taken into account.

To this aim we will adopt an indicator called *Intensity of Thermal Discomfort* for overheating ($\mathrm{ITD_{over}}$), introduced by Sicurella (Sicurella, 2012), which is defined as the time integral, over the occupancy period P (from 9:00 to 18:00 for weekdays in this case), of the positive differences between the current operative temperature and the upper threshold for comfort:

$$ITD_{over} = \int_{P} \Delta T^{+}(\tau)\, d\tau \tag{1}$$

where :

$$\Delta T^{+} = \begin{cases} T_{op}\ \tau - T_{lim}\ \tau & \text{if } T_{op}\ \tau > T_{lim}\ \tau \\ 0 & \text{if } T_{op}\ \tau < T_{lim}\ \tau \end{cases} \tag{2}$$

The value of the threshold temperature T_{lim} depends on the choice of a specific thermal comfort theory. In this paper, the adaptive approach is chosen, as described in the ISO EN 15251 Standard (EN Standard 15251, 2007): hence, the threshold value is not constant in time, but it should be determined daily as a function of the running mean outdoor air temperature T_{rm}. The formulation of the threshold temperature is given in Eq. (3), and corresponds to the fulfillment of Category I introduced by the EN Standard (high level of expectation):

$$T_{lim} = 20.8 + 0.33 \cdot T_{rm} \tag{3}$$

3 THE CASE STUDY

3.1 Description of the building

The building considered in this case study is an existing office building in Catania (Southern Italy), a town on the Eastern coast of Sicily, whose main features are summarized in Table 1. The ground floor hosts a series of offices used by the teachers of the local University, while the basement is occupied by laboratories; the roof is walkable and hosts the air-conditioning devices.

Table 1: Features of the building

General information	
Location	Catania, Italy (LAT. 37°31′N, LONG. 15°04′E)
Building type	Office building
Surface area	207 m^2
Operation hours	09:00-18:00 form Monday to Friday
Main orientation	NE-SO
Building envelope	
S/V ratio	0.47 [m^{-1}]
Walls – U value	U = 0.80 [W m^{-2} K^{-1}]
Roof – U value	U = 0.70 [W m^{-2} K^{-1}]
Floor – U value	U = 1.90 [W m^{-2} K^{-1}]
Windows – U value	U = 2.80 [W m^{-2} K^{-1}]
Shading	White blinds
Clay tiles – r value	0.25 [-]
Cool painting – r value	0.45 [-]

Figure 1: Ground plan with building orientation and picture of the main façade

The composition of the outer walls and the roof is reported in Table 2, from the outermost to the innermost layer.

The windows consist of double-glazing filled with Argon (4-12-4 mm), whose aluminum frame is provided with thermal cutting; the shading system consists of white curtains. The whole window system shows a thermal transmittance value U = 2.80 $W \cdot m^{-2} \cdot K^{-1}$, calculated according to (UNI EN ISO 10077-1, 2007).

In Table 2 the most important thermal properties of the building materials are also collected, as reported by the national standards (UNI 10351, 1994) and (UNI 10355, 1994), as well as by the international standard (UNI EN ISO 6946, 2008).

Table 2: Characteristics of the opaque envelope

Materials	**Thickness [cm]**	**Density [kg·m^{-3}]**	**Specific heat [J·kg^{-1}·K^{-1}]**	**Conductivity [W·m^{-1}·K^{-1}]**
Roof				
Clay shingles	1.2	1800	840	0.72
Mortar	2	2000	840	1.40
Sand	2	1700	840	0.60
Polyester membrane	0.8	1120	1460	0.16
Light cement screed	10	1600	880	0.65
Mineral wool	3	35	840	0.044
Reinforced base	6	2000	840	1.40
Prefabricated slab	6	2000	840	1.16
Air gap	30	1.20	1000	*
False ceiling	2	900	840	0.21
Outer walls				
Plates of basalt stone	3	2800	840	3.50
Mortar	3	2000	840	1.40
Concrete block	12	1400	880	0.43
Polystyrene	3	20	1400	0.036
Air gap	17	1.20	1000	**
Hollow clay block	8	750	840	0.40
Inner plaster	2	1400	840	0.70

*R = 0.23 [$m^2 \cdot K \cdot W^{-1}$] **R = 0.18 [$m^2 \cdot K \cdot W^{-1}$]

3.2 Description of the simulations

In order to simulate the dynamic energy performance of the building with EnergyPlus, the following assumptions were made:

- annual simulation period with hourly time step;
- the local weather file for the site of Catania is derived from the library available on the EnergyPlus weather data;
- occupancy pattern: from Monday to Friday, 09:00-18:00;
- electrical heat gains: 150 W per workstation;
- lighting systems: 6 $W \cdot m^{-2}$;
- people sensible load: 60 W per person;
- outdoor air infiltration rate: 0.5 h^{-1} during the occupancy period, 0.2 h^{-1} during the remaining time.

In the next section the results of the simulations will be presented under four different scenarios:

1. no painting (solar reflectance r = 0.25 for the non-treated existing roof);
2. cool painting actually applied on the roof (r = 0.45);
3. more performing painting (r = 0.65);
4. best performing painting (r = 0.85).

The simulations are focused both on the thermal comfort and energy performance of the building, as well as on the thermal behavior of the cool painting:

- the study of the thermal behavior of the cool painting estimates the temperature reduction of the roof outer surface;
- the comfort analysis shows the hourly evolution of the operative temperature for a reference room of the building. In addition, an indicator for measuring the duration and the intensity of thermal discomfort is calculated for three rooms with different exposures;
- the energy analysis evaluates the hourly heating and cooling loads, the design loads for summer and winter and the global annual energy need. In addition, a comparison between different heating systems will show the most performing equipment for the case study.

4 RESULTS AND DISCUSSION

4.1 Roof temperature

One of the most noticeable aspects related to the use of a cool painting on the finishing layer of a roof is the sharp reduction of its outer surface temperature: according to Levinson (Levinson, 2010), Romeo (Romeo, 2011) and Bozonnet (Bozonnet, 2011), a mean reduction of 12°C is expected when using a product with average quality (r = 0.45), whereas the use of a high-reflective painting (r = 0.85) can introduce a temperature reduction up to 25°C.
As concerns this case study, Figure 2 shows that the outer surface temperature for the existing roof is always higher than that reached by the painted roof. The minimum difference pertains to the less performing painting (r = 0.45) and ranges around 5-10°C, but in the case of the best performing painting such temperature difference actually increases up to 20-30°C.

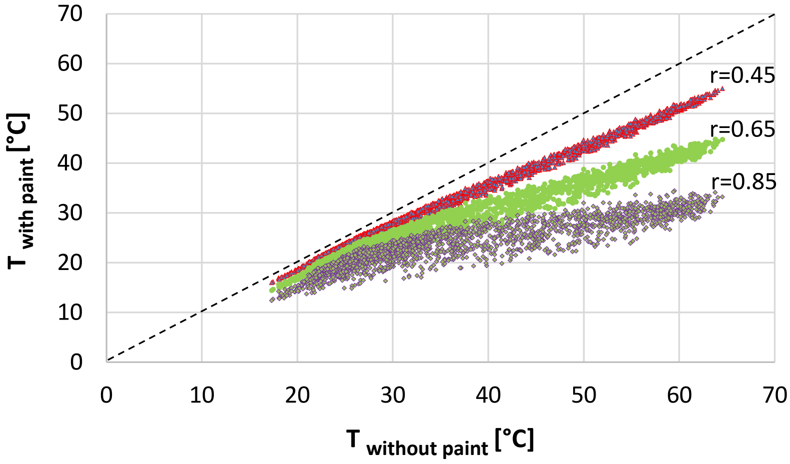

Figure 2: Comparison between the outer surface temperature of the roof without painting and with growing reflectance values

Furthermore, as shown in Figure 3 for the hottest days of the year, the use of a cool painting on the roof leads to a sensible reduction of the peak outer surface temperature, while at night the effect is more evident. In fact, when the solar irradiance is at its maximum (12:00 – 14:00) and a peak of about 60°C is reached for the untreated roof, a paint with r = 0.45 shows a reduction of 10°C and the one with r = 0.85 has a reduction of 25°C.
At night, these differences amounts to 1°C and of 3°C respectively, which lowers the risk of vapor condensation on the roof.

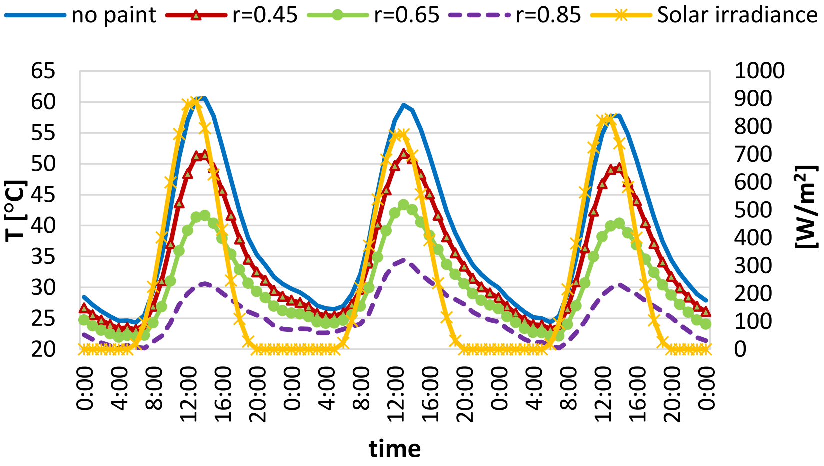

Figure 3: Outer surface temperature of the roof during the hottest days of the year (August 8th – 10th)

4.2 Comfort analysis

The sensible reduction in the surface temperature of the roof leads to a significant reduction in the operative temperature of the underneath rooms. The reference room for this analysis is the office n.3, placed in the middle of the northern side of the building (see Fig. 1). This office is representative of the whole set of offices due north-east.

As shown in Fig. 4, during the three hottest days of the year (from the 8th to the 10th of August) a peak value of 36°C for the operative temperature is expected without painting during the occupancy period (9:00-18:00); it can also be observed that a reduction of around 1 °C every Δr = 0.20 is achieved when using cool paintings with increasing reflectance.

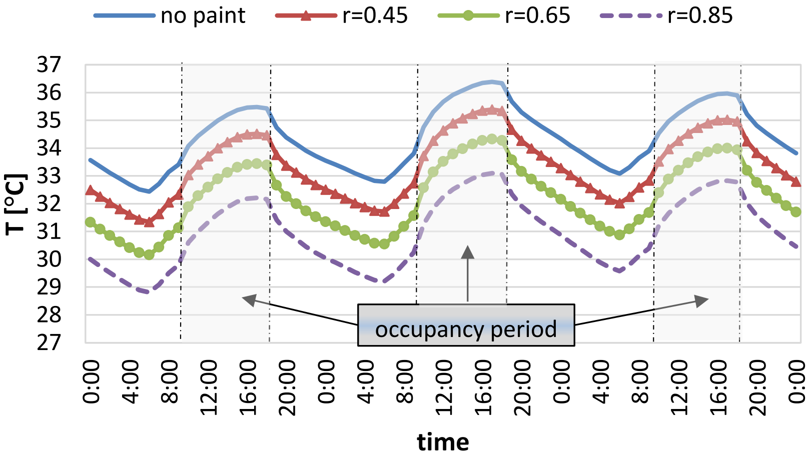

Figure 4: Operative temperature in the office n.3 during the hottest days of the year (August 8th – 10th)

In this case study, three rooms are investigated from the comfort perspective: the office n.3 which is representative of the north-east rooms, the office n.6 which is due south-west and the assembly room that is characterized by many glazed surfaces and by a double exposure.

The values of the ITD discomfort index, calculated as described in Section 2.2, are shown in Fig. 5. Here, the expected effectiveness of the real cool painting (r = 0.45) in reducing the thermal discomfort of the occupants is clear, as it implies a reduction of the ITD of about 21% with respect to the case without cool painting.

However, even better results can be obtained if using the most performing painting (r = 0.85), since the expected reduction of ITD is 63%, and this is true for all the rooms considered.

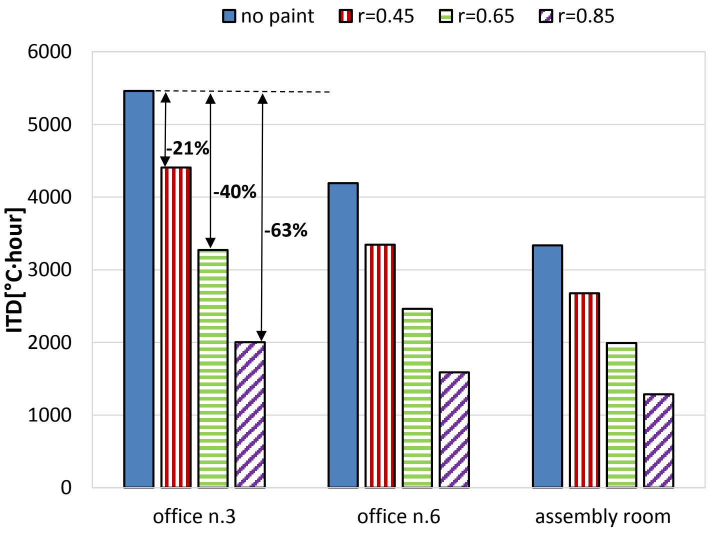

Figure 5: ITD index for three different rooms over the whole summer season

4.3 Energy analysis

Another positive aspect closely related to the use of the cool roof technology is the sensible reduction of the cooling load of the building, thanks to the lower rate of heat flux penetrating through the plain roof. This effect is shown in Fig. 6 with reference to the hottest days of the year; the curves represent the building sensible cooling load, determined through the simulations with a cooling set point temperature of 26°C during the occupancy period in summer (09:00 - 18:00 for weekdays, from May to September).

As one can observe, the peak of the cooling load can be cut by 14% in comparison with the case without cool painting if using the real paint with r = 0.45 (from 8440 W to 7230 W): The result is far more encouraging if using a very performing pain (r = 0.85), as the peak load is reduced by 44%, i.e. from 8440 W to 5206 W.

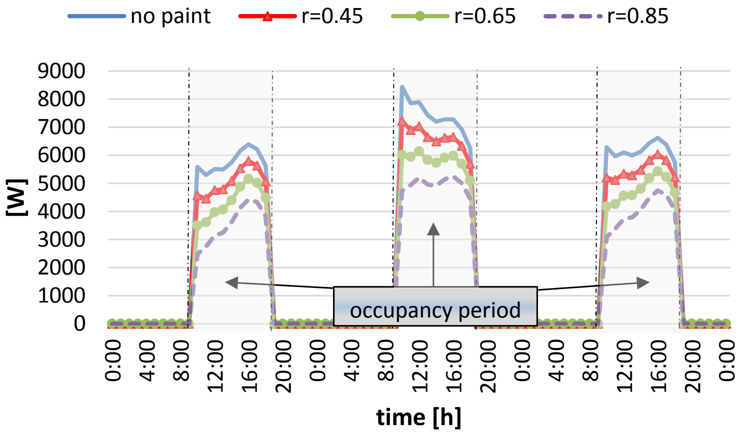

Figure 6: Sensible cooling load of the building during the hottest days of the year (August 8th – 10th)

However, the reduction of the cooling load in summer is not the only effect of the cool painting on the energy performance of the building. In fact, the low absorptivity of the roof also implies lower heat gains in winter, which determines a potential increase of the winter heating load. To this aim, the simulations were repeated for the winter season (from October to April), by imposing a heating set point temperature of 20°C during the occupancy period.

The resulting trend of the design thermal loads as a function of the solar reflectance *r* is reported in Table 3 for summer and winter: as a matter of fact, the increase of the peak heating load due to the presence of the cool painting in winter is not negligible. Actually, the peak heating load raises from 14.9 kW to 15.6 kW (+ 4.7%) if using a paint with r = 0.45, and from 14.9 kW to 17.1 kW (+ 14.7%) if using a paint with r = 0.85.

Table 3: Design thermal loads for heating and cooling

	r = 0.25	**r = 0.45**	**r = 0.65**	**r = 0.85**
Sensible cooling load [W]	8442	7299	6473	5613
Sensible heating load [W]	14885	15661	16299	17083

In any case, the most important parameter from the perspective of the overall energy savings is the annual energy need of the building for space heating and cooling, obtained by integrating over time the curves of the sensible load for heating and cooling.

As shown in Table 4, the annual energy need for space cooling Q_s is strongly reduced by increasing the value of the roof solar reflectance r : the expected reduction is around 15% if using a paint with r = 0.45, and around 45% for a paint with r = 0.85. On the other hand, an increase of the energy need for space heating Q_w should be expected (11% for a paint with r = 0.45 and 31% with r = 0.85).

As a result, the total expected annual energy need is reduced by 5% (from 8787 to 8347 kWh) and by 12% (from 8787 to 7742 kWh) in comparison with the case without cool painting, respectively when r = 0.45 and r = 0.85.

Thus, the results of the simulations seem to be very encouraging, and to justify the use of very performing cool painting for roofs in hot climates.

Table 4: Annual building energy need as a function of the solar reflectance of the roof

	r = 0.25	**r = 0.45**	**r = 0.65**	**r = 0.85**
Summer energy need Q_s [kWh]	5565	4726	3891	3042
Winter energy need Q_w [kWh]	3222	3621	4110	4700
Total energy need [kWh]	8787	8347	8001	7742

4.4 Comparison in terms of Primary Energy

From the previous analysis, one can conclude that the adoption of cool paintings always allows a reduction in the annual building energy needs in hot climates. However, in the authors' opinion this conclusion should also be supported by the calculation of the overall Primary Energy consumption.

In this case, one needs to define the plant solutions adopted to provide both heating and cooling to the sample building. In fact, the Primary Energy consumption (PE) strongly depends on the efficiency of the conversion process, which is expressed by the Primary Energy Ratio *PER*.

Now, in this study air-conditioning in summer is supposed to be provided through fan-coil units fed by a reversible electric air-to-water vapour-compression chiller. As concerns space heating, two different solutions will be investigated: air-to-water electric reversible heat pump and conventional gas-fired heat generator. The annual primary energy need for both cooling and heating need is expressed by the following equation:

$$PE = \frac{Q_s}{PER_s} + \frac{Q_w}{PER_w} \qquad (4)$$

Table 5: Primary Energy Ratio of different plant systems

	PER
Vapour-compression Chiller	PER_s = EER·0.46
Air-to-water Heat Pump	PER_w = COP·0.46
Gas-fired heat generator	$PER_w = \eta$

Here the first addend is the primary energy consumption for cooling in summer (S), while the second one is the primary energy consumption for heating in winter (W); the primary energy ratios PER_s and PER_w depend on the plant configuration and are summarized in Table 5.
For the calculation of the system efficiency, the following mean values were assumed:

- Energy Efficiency Ratio of the vapour-compression chiller: $EER = 3.65$;
- Coefficient of Performance of the heat pump: $COP = 3.76$;
- global efficiency of the gas-fired heat generator: $\eta = 0.75$;
- Italian electricity grid efficiency coefficient: 0.46.

As shown in Fig. 8, the primary energy demand for cooling (blue columns) always benefits from an increase in the solar reflectance of the cool painting. As concerns the primary energy demand for heating (red columns), its increase with r is less significant when using the heat pump than with a conventional gas-fired heat generator, thanks to the high PER of the heat pump. This allows an overall primary energy saving, as the annual PE drops from 5960 kWh without cool painting to 5289 kWh with a very performing painting ($r = 0.85$), so showing a reduction of 11%.
On the other hand, the use of a gas-fired heat generator leads to an increase of the overall primary energy need, so nullifying the benefits originating from the use of the cool painting in summer: the energy demand raises from 8068 kWh to 8461 kWh (increase of 5%).
These results suggest that the use of the cool roof technology has to be carefully evaluated also considering the winter period, and not only the summer period. The calculation should also account for the type of system adopted for space heating, since this choice may strongly influence the overall balance in terms of primary energy.

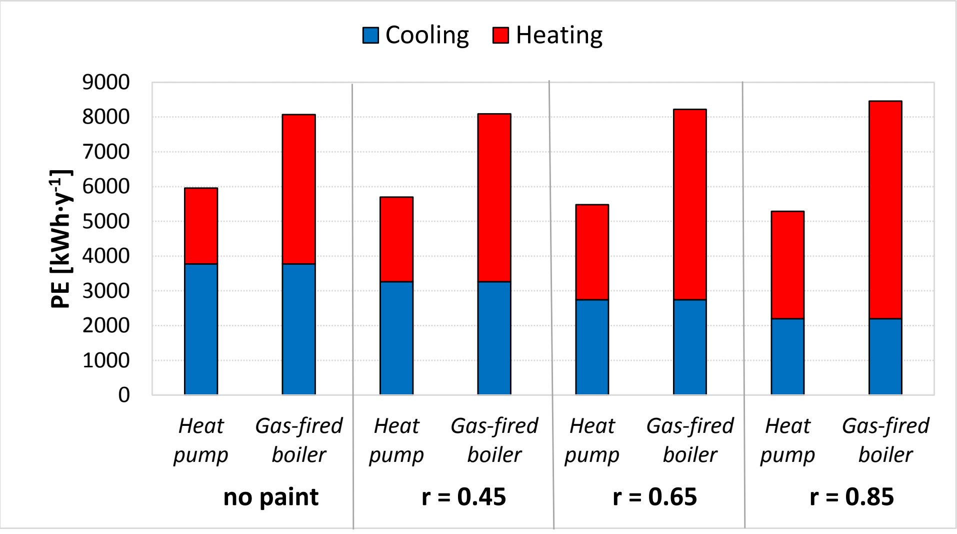

Figure 8: Comparison between different plant technologies in terms of annual primary energy need

5 CONCLUSIONS

The aim of this paper was to investigate the effectiveness of the cool roof technology for the refurbishment of an existing low-rise office building in Catania, a city in southern Italy with a hot-humid climate, in which the energy demand for space cooling in summer is predominant if compared to that for space heating in winter.

The simulations carried out with the software EnergyPlus have pointed out that the comfort sensation of the occupants in free running conditions in summer can be significantly improved by applying a cool painting with an average value of solar reflectance (r = 0.45), which corresponds to the performance of a commercial painting actually applied to the roof in the framework of an experimental campaign. However, further enhancements might be expected if using a very-performing cool painting (up to r = 0.85).

Moreover, the application of the cool painting leads to a noticeable reduction of the building energy needs for space cooling; however, an increase of the energy needs for space heating in winter should also be expected. Such a drawback provides a sensible increase of the primary energy consumption for heating, that may also overcome the advantages achieved in summer.

In conclusion, the adoption of cool paintings for roofs is a solution that must be carefully evaluated in regions with intense or long winter period and in buildings where the heating system has not a very high performance.

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