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|| PAPER ||

ENERGY AND ECONOMIC EFFICIENCY ANALYSIS OF THE USE OF COLD ROOFS FOR SOCIAL HOUSING RETROFITTING IN SOUTHERN SPAIN

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SUMMARY

Energy retrofitting of the housing stock is needed in order to reduce the consumption of the energy used to achieve comfort conditions and, this way, meet the objectives aimed at reducing the impact of energy consumption on climate change. In particular, the social housing stock built in Spain in the middle of the last century have poor conditions in terms of energy efficiency and its obsolete energy conditions make some type of retrofitting necessary in order to avoid indoor thermal discomfort and energy poverty situations. This study focuses on perform an energy and economic analysis, throughout the life cycle, of the use of cool roofs to retrofit the roofs of buildings belonging to the social park. The analysis is carried out on three cities, Seville, Malaga and Jaen, in the region of Andalusia, Southern Spain, representative of a wide range of the climatic conditions of this region. The findings of this work show noticeable energy and economic costs savings, which endorse the efficiency of the use of cold roofs to retrofit the roofs customary in social housing built in the central decades of the last century under the analyzed climatic framework.

Keywords: *Cool roof, Passive cooling, Energy efficiency, Social housing, Life cycle assessment*

1. INTRODUCTION

Over the last decades, a large number of institutions have warned of the exponential increase in energy demand and its consequent effect on climate change. This way, the European Commission stated that tackling energy consumption in European buildings is vital, Financing the Energy Renovation of Buildings with Cohesion Policy Funding (2014) [1]. According to this publication, nearly 40% of final energy consumption is attributable to buildings belonging to the public and private sector. Because of this, intensive research is being carried out aimed at reducing costs for the thermal conditioning of buildings in convergence with the directives set by the European Commission for H2030, 2030 Climate and Energy Framework (European Commission) [2].

In warm climates, as in the region of Andalucia, southern Spain, achieving indoor comfort during the hot season implies a very high energy consumption. Thus, it is necessary to implement energy efficiency measures that enable the reduction of the energy used for cooling. This is even more severe for the social park housing built in southern Spain in the middle of the last century, before the promulgation of the first Spanish legislation aimed at regulating energy demand in buildings, NBE-CT-79 (1979) [3]. In these buildings, there is an almost total absence of insulation in the envelope in general and in the roof in particular, which oftentimes leads to situations of discomfort and energy poverty.

Regarding the climatic characteristics of the considered geographical area, characterized by high levels of solar irradiation and low cloud cover throughout most of the year, cool roof systems seem very suitable in order to provide an efficient and inexpensive refurbishment of the buildings roofs belonging to the considered social park.

The "cool roof" is a roofing system able to reject a high percentage of solar radiation and that it carries out a high radiative exchange with the celestial vault, European Cool Roofs Council (Synnefa 2016) [4]. In this way a double effect is achieved: during daylight hours, the roof rejects a large fraction of solar radiation, which lowers its temperature noticeably and, at night, taking advantage of the lower sky temperature, it dissipates heat by means of long-wave radiative exchange with the sky.

The good properties of the cold cover to reduce energy consumption to achieve comfort conditions has been demonstrated in a large number of theoretical and experimental studies. Akbari et al. (2005) [5], through the monitoring of six different types of commercial buildings in California (USA), found that increasing solar reflectivity from 0.33 to 0.60 reduced noticeably peaks in interior temperatures and energy consumption for cooling during daylight hours. Likewise, Romeo and Zinzi (2013) [6] reported from experimental measurements that the application of a cold coat of paint reduced the cooling load by 54% for a roof with an area of 700 m^2, while the surface temperatures of the roof were reduced by 20 ˚C and 2.3 ˚C on the outer and inner surfaces respectively.

In the present work, it is performed an energy and cost-effectiveness analysis of the cold roof when it is used for the rehabilitation of common roofs in social housing built in the middle of the last century. The analyzes are developed for the lifespan of the cold coating layer whose application essentially constitutes the proposed retrofitting. The study is carried out for three cities in Andalusia, Southern Spain, which cover a large part of the climatic and geographical variety of the Andalusian capitals: Seville, Malaga and Jaen. It is worth noting that the results of this study can be extended to other geographical locations with climates similar to those studied, as is the case in most of the Mediterranean border areas.

2. STUDY CASES

This study considers a flat-type roof widely used in social housing in the period prior to the enactment of the first Spanish legislation on energy demand in 1979. The roof configuration is described in *Table 1*, where dimensioning and thermophysical characteristics of the roof components are shown. This roof configuration was considered as the reference case in the study in order to analyze the energy and economic savings when it is retrofitted to become a cool roof.

Three geographic locations representative of Andalusian geography have been chosen to carry out the study. They cover too a wide range of Andalusian climatic variability as is described in Section 3. They are the city of Seville, located in the Guadalquivir valley, the city of Malaga located on the Andalusian Mediterranean coast and the city of Jaen located in the interior of Andalusia and relatively far from coastal influences and influenced by the surrounding mountains. In *Figure 1* it can be seen the typical appearance of the flat roofs for some buildings built at the end of the 1960s in Seville (Spain), the Juncal neighborhood, representative of the type of housing studied in the present work.

The solar reflectivity of the outer surface of the reference roof has been taken equal to 0.8 and the thermal emissivity equal to 0.9, usual values of the type of material considered. The considered retrofitting process consists of applying a layer of white elastomeric paint with a solar absorptivity of 0.1 and a thermal emissivity of 0.92.

3. **CLIMATIC FRAMEWORK**

In Southern Spain the clime is characterized by a high seasonality. Thus, summers are usually dry and hot, while winters tend to have moderate temperatures when compared to the usual records in central and northern Europe. Spring and autumn are characterized by having mild temperatures and by concentrating most of the annual rains. *Figure 2* shows the monthly averages of the minimum and maximum temperatures in the three cities studied.

As regards solar radiation, its normal direct component is fairly uniform throughout the year. However, as it is shown in *Figure 2*, the irradiation on a horizontal surface is much higher in summer than in winter, due to the difference in the angle of incidence, much more perpendicular in summer, and the greater number of hours of sunlight.

On the other hand, the sky temperature reaches its minimum values in cold seasons and its maximums in warm months, as seen in this figure, which shows its monthly averages. However, in *Figure 3* it is observed that in the warmest season, a time in which it is convenient to take full advantage of the characteristics of cold roofs, there is a notable variation for the sky temperature throughout the day, so that it reaches its maximum peaks in the central hours of the day and their minimums at dawn or near dawn. As can be seen in the figure, this variability can be up to 20 ˚C which it is of great importance, because thanks to the low values

Layer	Description	Thickness (m)	Density (kg/m^3)	Specific Heat ($J/kg\,K$)	Conductivity ($W/m\,K$)
1 (Ext)	Bituminous paint	0.0015	1150	1000	0.23
2	Ceramic tiles	0.005	2000	800	1.00
3	Mortar	0.01	2000	1000	1.40
4	Protective Layer)	0.015	1150	1000	0,23
5	Mortar	0.01	2000	1000	1.40
6	Carbon cinders	0.1	640	657	1.40
7	Lightweight concrete	0.15	1200	1000	0.57
8	Concrete vault	0.30	1330	1000	1.32
9 (Int.)	Gypsum plaster	0.01	1000	1000	0.32

Table 1. Roof thermophysical characteristics. The values shown in this table were obtained from the Spanish Technical Code, Prontuario de Soluciones Constructivas [7] and from Fernández Díaz (2019) [8].
Source: Own elaboration.

it takes during the night, the thermal energy accumulated in the roof layers can be dissipated, allowing the so called radiative cooling.

The Spanish Technical Building Code in its Energy Saving chapter, section on Limiting Energy Demand (CTE-HE1), explicitly provides the climatic zone of the 50 provincial capitals and the autonomous cities of Ceuta and Melilla. In this classification, winters are classified as A, B, C, D and E, and summers as 1, 2, 3 and 4, both according to increasing order of climatic severity. Based on this classification, the city of Malaga is classified as A3, Seville as B4 and Jaen as C4.

For all towns in Andalusia, the climatic severities range from A to D for winter and 2 to 4 for summer. However, none of the cities reaches winter severity D. For this reason, the three selected capitals cover, in addition to three representative geographical locations in Andalusia, a large part of the range of variability of the most common climatic classifications for the Andalusian province capitals.

4. **METHODOLOGY FOR CALCULATING THE ENERGY BEHAVIOR OF THE ROOF**

4.1 **Modeling of heat transfer through a multilayer roof**

The heat flow through the multilayer roof is determined by the following energy processes:

- Heat gain on the outer slab due to solar irradiation.
- Heat exchange by radiation between the outer surface and the sky and the environment.
- Heat exchange by convection between the outer surface and the ambient air.
- Heat transfer by conduction through the layers of the roof.
- Heat exchange by convection and radiation between the internal surface of the roof and the

Fig. 1. Buildings from the Juncal neighborhood, Sevilla, (Spain). Source: Own elaboration.

interior of the building.

When establishing the physical model, it must be borne in mind that all energy processes take place simultaneously. Therefore, the equations of heat transfer through the different layers of the roof and the equations of convective and of radiative exchange must be calculated at each time step. So, in every step of time, first the energy balances on the surfaces are computed and then they are used as boundary conditions for solving the diffusion equation that describe the heat transfer through the roof layers.

4.2 **Convective heat transfer coefficients**

The convective heat transfer coefficient used for heat exchange between the external surface of the roof and the ambient air is that proposed by Hagishima and Tanimoto (2003) [9] given by

$$h_c = 8.18+2.28\,U_R \qquad \mathrm{W/m^2\,K}$$

being U_R the wind speed in m/s measured at a distance of 0.6 m above the roof. This correlation is based on experimental measurements on flat roofs, so it is well adapted to the case study considered in this work.

To calculate the convection heat transfer between the internal surface and the interior air of the building, it has been used a mixed convection-radiation heat transfer coefficient given by $h_i = 8.3$ W/m² K, as recommended by ASHRAE (1997) [10].

4.3 **Calculation of the downward long-wave radiation of the sky**

The global thermal balance of the roof is highly influenced by the radiative exchange with the sky. This usually has a lower temperature than air, and in summer times, when ambient temperatures and solar irradiation contribute to storing thermal energy in the roof, radiative exchange with the sky is able to cool the roof that influences its thermal behavior.

In the present work, the downward long-wave radiation of the sky has been calculated using the expression.

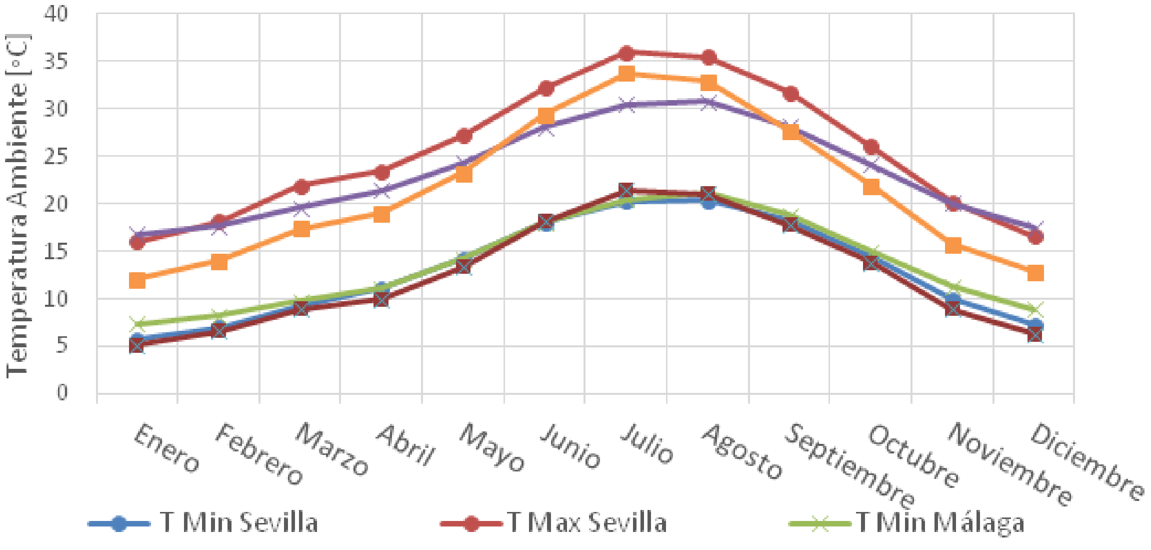


Fig. 2. Monthly averages of maximum and minimum temperatures. Source: Own elaboration.

$$Q_{sky} = (1 + K \cdot C^2)\ \ 8.78\ 10^{-13}\ \ T_{amb}^{5.852}\ \ RH^{\,0.07195}$$

This correlation is a variant of the Swinbank model han was developed by Goforth et al. (2002) [11]. Here, K is a parameter that depends on the height of the cloud layer, C is the percentage of cloudiness, being 0 for fully clear skies and 1 for completely cloudy skies, T_{amb} is the ambient temperature and finally, RH is the relative humidity.

The values of the variables needed to compute Q_{sky} have been taken from values provided by different climatic organisms: the Spanish Meteorological Agency, the Meteorological Services of the National Aeronautics and Space Administration (Nasa) and the National Oceanic and Atmospheric Administration (NOAA).

4.4 **Loss of solar reflectivity due to the aging of the cool roof**

The aging effect results in a loss of up to 20% of the reflectivity of the cold paint layer along the first three years, then it tends to stabilize. Maintenance, when an intensive washing process is applied, recovers up to 90% of said reflectivity, Zielnik, A. (2008) [12].

Therefore, this aging effect must be included in the calculation of the heat transfer through the roof in order to assume realistic conditions.

In this work, due to the economic cost that this implies, a 10-year wash has been considered. More details on the aging process and its impact on the energy performance of the cool roof can be found in Domínguez-Delgado et al. (2020) [13].

4.5. **Numerical resolution**

In order to carry out the numerical resolution of the equations described in the previous sections, an one-dimensional spatial discretization of the roof has been used so that the border nodes are placed on the roof internal and external surface layers.

The values of the temperature in the interior nodes are calculated from the finite difference

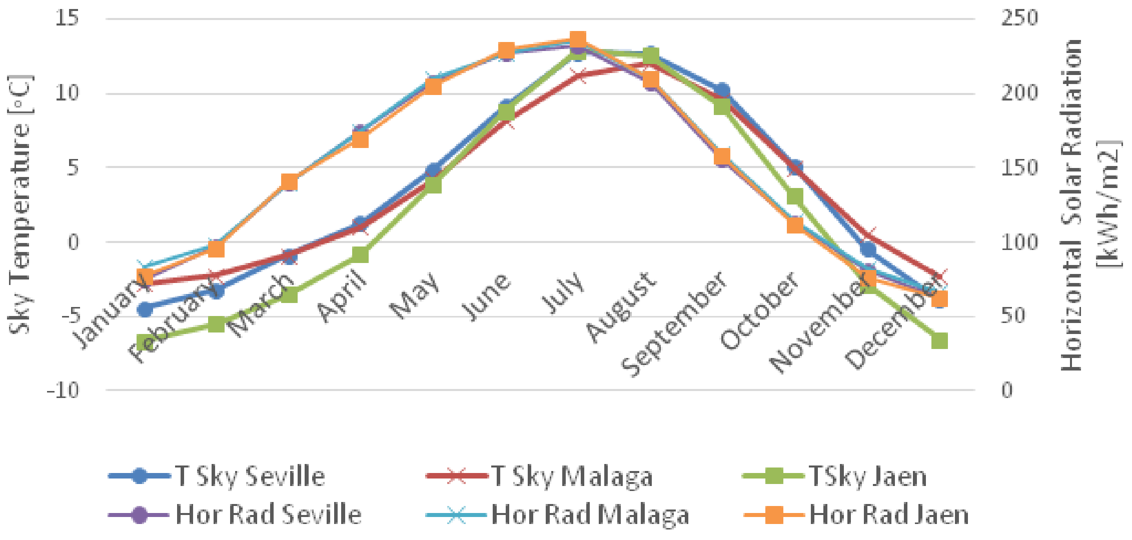


Fig. 3. Monthly averages of solar radiation on horizontal surface and sky temperature. Source: Own elaboration.

approximation of the heat conduction equation. At the border nodes, the appropriate boundary conditions are established by means of energy balance equations that take into account the processes of long-wave radiative exchange, convection with indoor and outdoor air, and solar radiation in the case of the roof outer layer. For the time discretization a semi-implicit Euler was used.

For the calculations, constant interior temperatures have been assumed in each season of the year. Specifically, the considered temperatures are 20 ˚C for the cold season, 24 ˚C for the warm season and 22.5 ˚C for the intermediate seasons. These values have been selected taking into account the comfort temperature intervals established in the Spanish regulation of thermal installations for buildings (RITE) [14].

5. METHODOLOGY FOR THE LIFE CYCLE COST-EFFECTIVENESS ANALYSIS

In order to make an accurate estimate of the economic implications of the refurbishment by using cool roofs, a cost-effectiveness analysis through the life cycle of the cool coat has been used in this work taking into account future costs, Duffie y Beckman (2006) [15].

To carry out this analysis, all the anticipated costs throughout the period of time covered by the life cycle are calculated and discounted at their present value. The procedure followed is that of calculating the costs in each of the future years covered by the study and then discounting them at their present value.

Then, after the costs derived from the installation, the maintenance and the energy consumption are calculated for the whole lifespan, the cost-effectiveness is evaluated. The

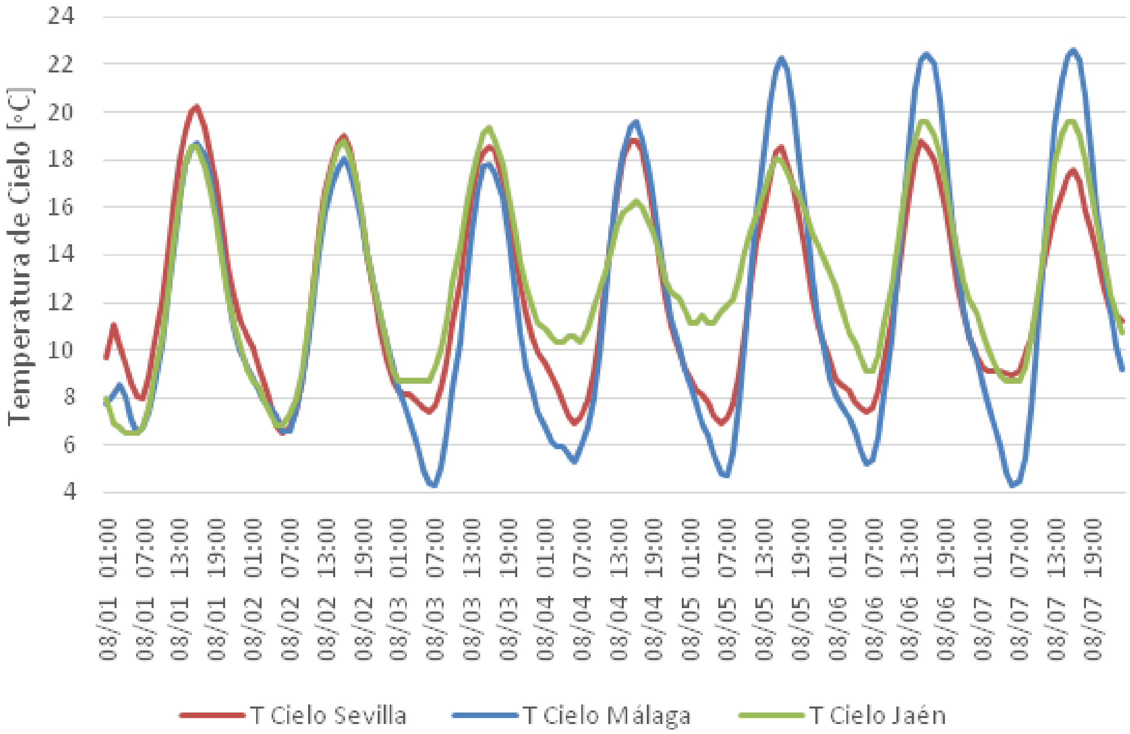


Fig. 4. Sky temperature of a summer week. Source: Own elaboration.

lower the cost during the life cycle, the greater the cost-effectiveness of using the considered roof. The difference between the calculated costs for cool roofs and for the reference roof is the savings produced by the proposed refurbishment.

To perform the analysis, we considered a lifetime of $n = 20$ years, that is the average life service of the considered reflective layer, Cype (2017) [16]. Then, based on the calculation of the total cost during the life cycle, the savings with respect to the reference roof and the period of return on the investment have been calculated for each of the studied cases.

To calculate the present worth of one monetary unit of the future time period k (usually expressed in years), with a market discount rate d (fraction per time period), the relationship to be used is:

$$PW_k = 1 / (1+d)^k \quad .$$

So the current cost of any energy cost $C_e(k)$ due to energy consumption in year k is given by

$$PW_k(C_e(k)) = \frac{(C_e(k))}{(1+d)^k} \qquad ,$$

being

$$C_e(k) = \left(\frac{(Q_C(k) \cdot P_e)}{(COP_C \cdot (3.6 \cdot 10^6))} + \frac{(Q_H(k) \cdot P_e)}{(COP_H \cdot (3.6 \cdot 10^6))} \right) (1+i)^{k-1}$$

where COP_C y COP_H are the energy efficiency indices for cooling and heating respectively, $Q_C(k)$ y $Q_H(k)$ the energy consumption per m^2 for cooling and heating respectively during year k, P_e the initial price of the energy used, electricity in the present study, and i the annual inflation rate for the price of energy.

Then, the present value of the total cost per m^2 for the whole time period of the life cycle is given by

$$C_t = \sum_{(k=1)}^{20} PW_k(C_e(k)) + C_I + C_M$$

where C_I y C_M are the installation and maintenance costs respectively.

The difference between the value of C_t calculated for the reference roof and the cool roof provides the net savings (NS) for the whole life cycle period.

Finally, the Payback Period (PB) is calculated as the time horizon t for which the value of NS becomes equal to zero.

The variables considered to perform the economic calculations involved in the life cycle costs analysis are listed in *Table 2.*

The costs of the cool paint application and its maintenance were taken from CYPE Engineers Construction Price Generator (2017) [16]. The electricity price was the price in Spain (including taxes) for household consumers, Eurostat (2020) [17]. Inflation and discount rates are reference values used in other studies on the life cycle analysis of buildings retrofitting, Saafi y Daouas (2018) [18] and Nydahl et al. (2019) [19].

Finally, the energy efficiency values considered for the air conditioning machinery were

$COP_C = 3.2$ and $COP_H = 3.6$ corresponding to commercial machinery of efficiency energy type labeled A available in the market.

6. **RESULTS**

6.1 **Energy Results**

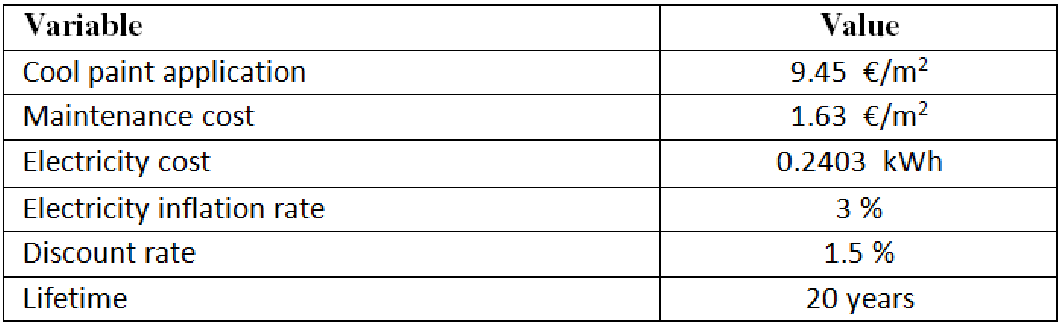
In this section, the energy performance of the cool and the reference roofs are analyzed for all the case studies considered.

In *Figure 4*, monthly heat fluxes are shown in MJ per m^2, considering inward heat flux as positive and outwards flux as negative. The values shown in the figure are the corresponding to the first year after the cool paint application. In the following years, the values of the monthly loads vary slightly when compared to the first year values, owing to the aging process of the outer layer, which results in a loss of solar reflectivity.

As it can be seen in this Figure, in all the cases the reference roofs have higher cooling loads than the cold roofs, in accordance with the desired effect of reducing these loads, mainly in the warm season. However, the low absorptivity of the cold cover produces a penalty in winter that causes an increase in the heating loads for the cool roofs with respect to the reference ones. This combined effect forms the basis for estimating the energy savings achieved by using cool roofs, if it occurs.

Figure 5 shows the loads in GJ/m^2 for the whole life cycle time period for all the studies cities. The gradual process of solar reflectivity loss caused by the aging effect of the reflective paint layer has already been taken into account in the calculation of the loads. As can be seen, in all cases there is an increase in the heating load for the cool roofs when compared to the reference roof and the opposite phenomenon for the cooling load. But the most relevant fact is that, in all cases, the installation of the cold layer reduces the total load in relation to the reference roof. As can be seen in this figure, the highest total loads are in the city of Jaen, followed by Seville, while the city of Malaga has the lowest loads, both for the cool and for the reference roofs.

Figure 7 shows the energy savings in GJ/m^2 and in percentage reduction, for the whole life cycle time. As can be seen, the city of Seville is the one with the highest energy savings in absolute terms, although the percentage of reduction in the city of Malaga is similar, about 30%



Variable	Value
Cool paint application	9.45 €/m^2
Maintenance cost	1.63 €/m^2
Electricity cost	0.2403 kWh
Electricity inflation rate	3 %
Discount rate	1.5 %
Lifetime	20 years

Table 2. Economic variables used in the life cycle analysis. Source: Own elaboration.

for both cities. On the other hand, Jaen is the one that produces the lowest yields due to the penalty that occurs in the heating load in winter. Even so, it achieves a savings rate close to 22%.

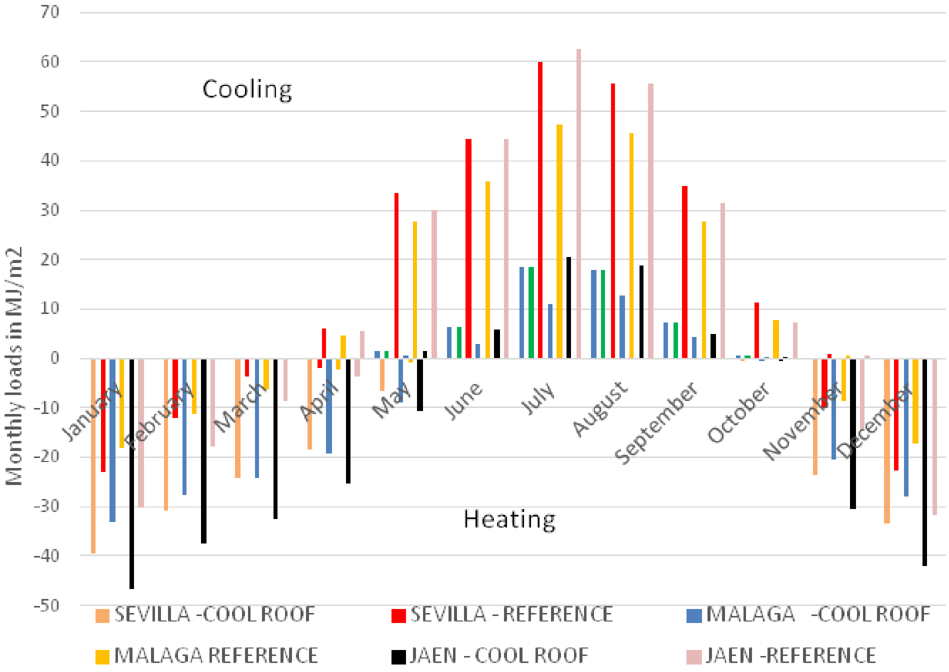
6.2 **Economic results**

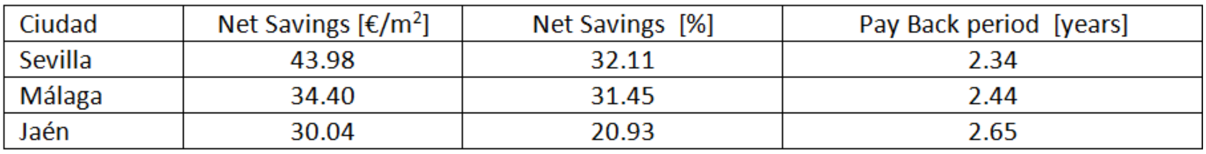
This section presents the economic results for the life cycle period of time using the AN and the PA as economic indicators.

The net savings and payback period when the cool roof is used to retrofit the reference roof, were calculated under the economic framework described in Section 5 and using the energy results described in Section 6.1.5.

To calculate the possible savings associated with the use of the cool roofs it has been considered that the retrofitting of the reference roof was necessary. Therefore, the installation of the reflective paint layer has been considered as an optional alternative to the use of another bituminous waterproofing paint, usual in the restoration of flat roofs. In this way, the costs associated with the rehabilitation are calculated as marginal costs, that is, as the difference between the installation of the cold paint and the common bituminous paint. For the latter, a cost of 8.01 €/m^2 has been used, CYPE (2017).

Table 3 shows the net savings in €/m^2 for the considered life cycle period of 20 years, as well as the percentage savings compared to the reference roof and the payback period for the





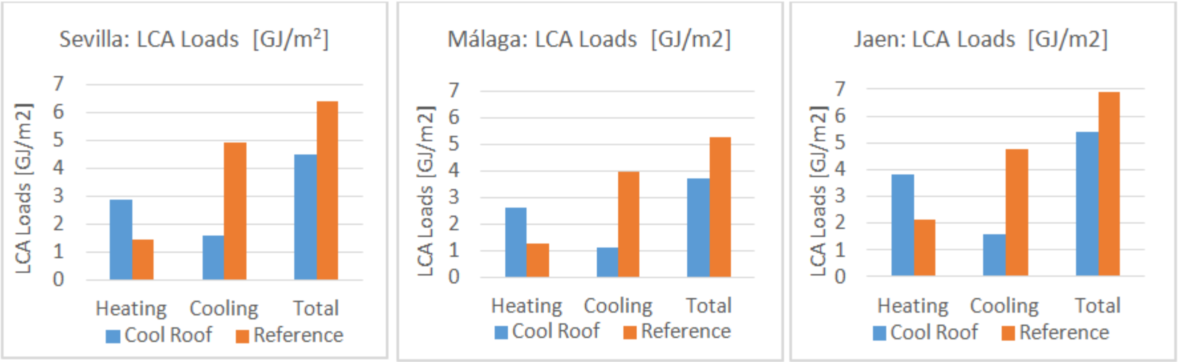
Ciudad	Net Savings [€/m^2]	Net Savings [%]	Pay Back period [years]
Sevilla	43.98	32.11	2.34
Málaga	34.40	31.45	2.44
Jaén	30.04	20.93	2.65

Fig. 5. Monthly heating and cooling loads for reference and cool roofs. Source: Own elaboration.
Table 3. Economic results for the life cycle period. Source: Own elaboration.

investment made. The remarkable fact is that all cases give positive net savings values. In short, for the considered life cycle period, net savings values equal to 43.98 €/m^2 for Sevilla city, to 34.40 €/m^2 for Málaga city and to 30.04 €/m^2 for Jaén city are found. These results give savings percentages for the cool roofs when compared to the reference roofs equal to 32.11%, to 31.45% and to 20.93% respectively for Sevilla, Málaga and Jaén and payback periods of 2.34, 2.44 and 2.65 years respectively.

7. **CONCLUSIONS**

From the energy analysis carried out, it is concluded that the use of the cool roof, in the three cities under study, produces a decrease in the energy flow through it when compared to the reference roof. This decrease is approximately 30% for the cities of Seville and Malaga, and it reaches somewhat lower values, close to 22%, for the city of Jaén. This is mainly due to the difference between the cities in the penalty values at winter that causes a greater load for heating in Jaén.



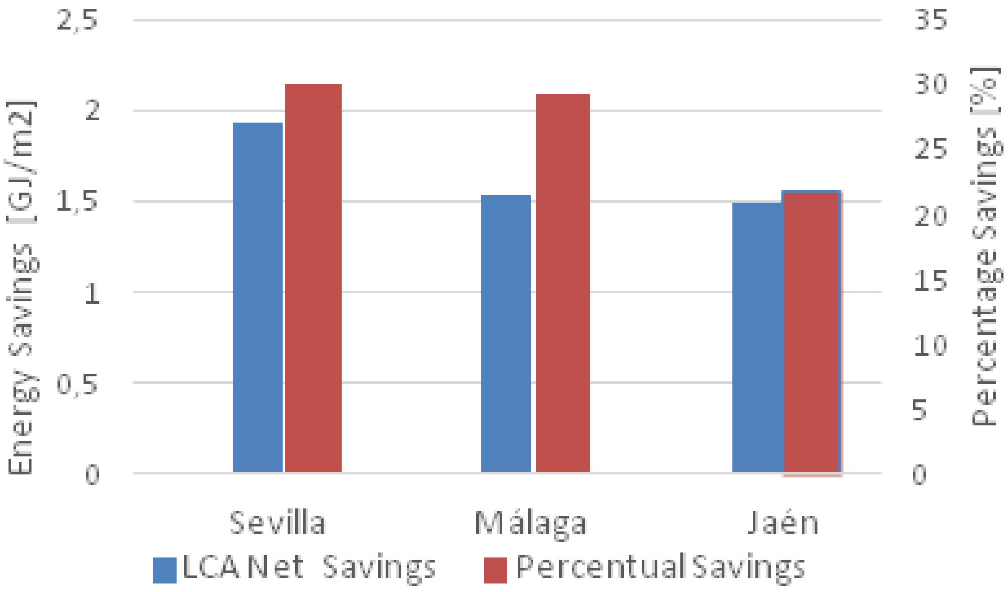


Fig. 6. Loads in GJ/m^2 for the life cycle period. Source: Own elaboration.
Fig. 7. Savings in GJ/m^2 and in percentage for the entire life cycle period. Source: Own elaboration.

From the life cycle cost-effectiveness analysis made, it is concluded that refurbishing a roof with the typology of the reference roof, by using cool roofs, is cost efficient with net savings for the life cycle period ranging from 32.11% for Seville and 20.93 % for Jaen.
Therefore, as a final conclusion, it can be established that for the three cities considered, representatives of a large part of the climatic and geographic zones of Andalusia, Southern Spain, the retrofitting of roofs common in social housing prior to the first Spanish legislation regulating energy demand in buildings, by using cool roofs, it provides significant energy savings and is cost-efficient for the period of the life cycle considered. Therefore, it is a suitable refurbishment measure both from the energy point of view, with the implications that this entails of environmental nature and climate change, and from the economic perspective, being an interesting refurbishment measure from the point of view of costs for the social housing owners.

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