sustainability

MDPI

Article

Energy and Economic Life Cycle Assessment of Cool Roofs Applied to the Refurbishment of Social Housing in Southern Spain

Antonio Dominguez-Delgado [1,*] and Helena Domínguez-Torres [2] and Carlos-Antonio Domínguez-Torres [3]

1 Department of Applied Mathematics 1, Escuela Técnica Superior de Arquitectura, Universidad de Sevilla, Avda. Reina Mercedes 2, 41012 Sevilla, Spain
2 Facultad de Económicas, Universidad de Sevilla, Avda. Ramón y Cajal, 41012 Sevilla, Spain; heldomtor@alum.us.es
3 Escuela Técnica Superior de Arquitectura, Universidad de Sevilla, Avda. Reina Mercedes 2, 41012 Sevilla, Spain; cardomtor@alum.us.es
* Correspondence: domdel@us.es

Received: 8 June 2020; Accepted: 6 July 2020; Published: 12 July 2020

check for updates

Abstract: Energy refurbishment of the housing stock is needed in order to reduce energy consumption and meet global climate goals. This is even more necessary for social housing built in Spain in the middle of the last century since its obsolete energy conditions lead to situations of indoor thermal discomfort and energy poverty. The present study carries out a life cycle assessment of the energy and economic performance of roofs after being retrofitted to become cool roofs for the promotion of social housing in Seville (Spain). Dynamic simulations are made in which the time dependent aging effect on the energy performance of the refurbished cool roofs is included for the whole lifespan. The influence of the time dependent aging effect on the results of the life cycle economic analysis is also assessed. A variety of scenarios are considered in order to account for the aging effect in the energy performance of the retrofitted cool roofs and its incidence while considering different energy prices and monetary discount rates on the life cycle assessment. This is made through a dynamic life cycle assessment in order to capture the impact of the aging dynamic behavior correctly. Results point out significant savings in the operational energy. However, important differences are found in the economic savings when the life cycle analysis is carried out since the source of energy and the efficiency of the equipment used for conditioning strongly impact the economic results.

Keywords: cool roof; energy efficiency; social housing; energy saving; dynamic numerical method; life cycle assessment

1. Introduction

Over the last few decades, there has been growing concern about global energy demand due to the exponential increase in its consumption. As stated in the document [1] from the European Commission, tackling energy consumption in European buildings is vital. According to this publication, nearly 40% of final energy consumption is attributable to buildings across the public and private sector. Because of this, extensive research in the field of energy efficiency has focused on the need to reduce energetic costs in the thermal conditioning of buildings in order to meet the directives set by the EU for H2030 [2], which establishes as a target for 2030 an improvement in energy efficiency of at least 32.5%.

In this research framework, the work focused on the use of techniques that take advantage of environmental and climatic resources in a suitable form is noteworthy. In warm climates, as in southern Spain, the high energy consumption needed to obtain internal comfort in buildings during the hot season poses a major problem. This is especially severe for the case of the social park housing built in southern Spain before the implementation of the first Spanish legislation aimed at regulating energy demand in buildings, NBE-CT-79 [3]. In this housing, the envelopes in general, and the roofs in particular, lack thermal insulation. Taking into account that in this region of Spain, the climate is dry and warm in the cooling season with usually clear skies at this time of year, it seems appropriate to take advantage of the radiative exchange with the sky by means of cold roof techniques to reduce the cooling load.

The European Cool Roofs Council [4] defines a "cool roof" as a roofing system able to reject solar heat and keep surfaces cooler under the sun. A "cool roof" is usually obtained by applying cold materials to the external surface of a roof. Its thermal performance is due to the properties of these materials, which are characterized by high values of solar reflectivity and thermal emissivity. Thereby, these kinds of materials are able to reduce the solar radiation absorption while releasing the heat absorbed by the roof. This way, during the day, the amount of absorbed solar radiation is reduced, and during the night, there is roof cooling because of the radiative exchange with the sky, which usually is colder. Thus cool roofs are considered a passive radiative cooling technique [5,6].

For cold materials, there are slightly differing definitions. Thereby, for ES-ENERGY STAR [7], cold materials must have a solar reflectance initially equal to or higher than 0.65, and after three years, it must be higher than 0.50, whilst APEC Energy Working Group [8] considered that they should have at least a reflectance of 0.70 and a thermal emissivity of 0.75.

The usefulness of cool roofs to enhance comfort conditions and reduce energy consumption in dwellings and more collective use buildings, schools, office buildings, libraries, etc., has been highlighted in a large number of experimental and theoretical studies. For example, Akbari et al. [9] monitored six types of commercial building roofs in California (USA) and found that increasing the solar reflectance of roofs by 0.33–0.60 reduced the peak temperatures by 33–42 °C and the daily cooling energy consumption by 4%, 18%, and 52% in a cold storage facility, a school building, and a department store building, respectively. Romeo and Zinzi [10] reported from field measurements that the application of a cool paint reduced the cooling load by 54% for a roof with an area of 700 m^2, while the peak temperatures of the external roof surface and the indoor air were reduced by 20 °C and 2.3 °C, respectively.

However, the extent of the benefits obtained by the use of cool roofs is found to depend on the local climatic conditions and on a number of other factors such as energy prices, the conditioning equipment, the building use, and the aging effect of the roof coating [11–22]. Likewise, benefits resulting from the decrease of the heat island effect together with an improvement of comfort in urban environments have been shown [13,14,17].

From an economic perspective, in [23], the usefulness of cool roofs was shown to produce significant savings when used to retrofit commercial buildings in the USA. Likewise, Reference [19] found that a high scale implementation of cool roofs in Andalusia, in the south of Spain, could potentially save, considering only residential buildings with flat roofs using electrical heating, 59 million euros annually in electricity costs, and the emission of 136,000 metric tons of CO_2 could be directly avoided every year from the production of electricity.

By contrast, only a limited number of studies have dealt with with the cost-effectiveness of cool roofs based on life cycle analysis. In [24], the cost-effectiveness of reflective white and colored roofs compared to conventional gray roofs in six selected cities in Mexico was analyzed. Based on the costs of electricity and reflective materials, a 10 year life cycle cost analysis showed that, in the absence of insulation, reflective white and colored roofs were more cost-effective than gray roofs for all locations. Zhang et al. [25] demonstrated the cost-effectiveness of using a cool paint in both unventilated and ventilated concrete roofs under the tropical climate in Singapore. Jo et al. [26] carried out research by including both on-site data and a building energy simulation model in order to quantify the electricity savings of a commercial building when replacing the existing dark roofing material with a reflective cool roof system. A 20 year cost benefit analysis, including the additional costs of cool roof retrofit and maintenance, showed that a 100% cool roof installation resulted in a savings of approximately $22,000 per year in energy costs and a consequent nine year payback period for the added cost. Yuan et al. [27] stove to find an optimal combination of the surface reflectivity and the insulation thickness of exterior walls based on a 10 year life cycle cost analysis. Optimum combinations of surface reflectivity and insulation thickness for six different regions in Japan were proposed.

However, the long-term performance of the reflective material was not taken into account in most of the papers referenced. In [28], a 20 year life cycle cost analysis proved that the cost-effectiveness of aged and restored cool roof when used to retrofit non-insulated roofs led to a net savings of up to 44.53 Tunisian dirhamsper m^2 and a payback period of 3.4 years. This work showed the interest in performing life cycle analysis in order to draw energy and economic conclusions. In [29], a new and structured approach was developed to carry out an uncertainty and sensitivity analysis in Life Cycle Assessment (LCA) in order to support the decision-making process in building renovation. Likewise, in [30], a life cycle assessment was used in order to make an economic-environmental valuation of a standard energy retrofit project for a public building in a Mediterranean area.

Moreover, the energy efficiency improvements that are achieved by means of the refurbishment of roofs when becoming cool roofs can be framed into sustainable energy transitions and the decarbonization process. However, the sustainability of an action whose aim is to improve energy efficiency must be ensured for its entire life cycle [31].

Considering that the energy refurbishment of the housing stock is needed in order to reduce energy consumption and that this is especially much more necessary for social housing built in Spain in the middle of the last century that has obsolete energy conditions, leading to situations of indoor thermal discomfort and energy poverty, the analysis carried out in this work tries to clarify the pertinence of using cool roofs as an efficient measure to reduce the energy consumption to obtain indoor comfort conditions for the considered housing park.

In the present paper, a study is proposed in order to appraise in a deeper way the effect of the aging on the energy performance of cool roofs, as well as the implications for the economic and energy life cycle assessment of this kind of roof when applied to the refurbishment of the social housing stock considered. This requires specific simulation codes that allow the incorporation of aging patterns to calculate the energy dynamic of the cool roof accurately when its solar reflectivity decreases because of the aging effect. Commercial packages for building energy simulation do not incorporate this ability, and this gap requires the development of specific simulation codes like the one presented here. This software limitation can be the cause of the absence of studies dealing with numerical computations of the time dependent aging effect for cool roofs. To the best of our knowledge, there exists a gap in the literature with regard to studies that perform dynamical life cycle assessment of cool roofs and analyze its energy and economic implications when used for the refurbishment of social dwelling roofs. Such a gap is particularly relevant in the geographical area that is analyzed here and that is characterized by high cooling demands.

This way, a comprehensive numerical study is done to simulate the energy performance of cool roofs when used to retrofit roofs from residential buildings belonging to the social park housing built in Seville, Spain, before the implementation of the first Spanish legislation aimed at regulating energy demand in buildings, NBE-CT-79 [3], in 1979. The main objective is to perform an energy and economic life cycle assessment of the cool roofs in a broad framework taking into account the effect on the LCA results of the real weather of Seville, the long-term performance of the coating layer solar reflectivities, the energy and equipment types used for conditioning the buildings, and the impact of economic parameters. Regarding the choice of the case study, it was taken into consideration that the weather of Sevilla makes this city a good place to analyze the potential advantages of the use of cool roofs in order to reduce energy consumption to achieve interior comfort conditions. Finally, it is necessary to point out that the findings of this study can be extended to other geographic scenarios as long as they are characterized by similar weather conditions to those existing in Sevilla. This would be the case of southern Spain and most of the meridional regions of Europe.

2. Methodology to Estimate the Roof Energy Performance

2.1. Physical Model

In this section, a generic description of the physical problem involving the heat transfer through the roof is set out. Specifically, the heat transfer in the roofs is determined by:

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

Other possible factors, such as the radiative exchange between the roof and adjacent buildings or vegetable masses higher than the studied building, were not taken into account in this study for the sake of brevity.

In order to establish the physical model, the fact that the equations describing the heat diffusion equations through the different layers of the roof and the radiative exchanges must be computed in each time step in order to approximate the heat transfer through the roof adequately must be taken into account.

Heat exchanges between surfaces and air were calculated by using convective heat transfer correlations based on the use of suitable convective heat transfer coefficients together with the equations given by the energy balance for the external roof surface; see Section 2.2.2. Internal roof surface energy balance calculation was done by taking a fixed room temperature T_{room} constant for each season. Then, we calculated the exchange of heat by convection and radiation between the internal roof surface and the interior of the building by using a combined convective-radiative transfer coefficient and the energy balance for the internal roof surface; see Section 2.2.2.

2.2. Mathematical Formulation

In this section, the mathematical equations involved in the heat transfer through the roof are explained.

2.2.1. Thermal Conduction through the Roof

Heat conduction through the envelope is modeled by the equation:

$$\rho\, c_p \frac{\partial T}{\partial t} = \nabla \cdot (\kappa \nabla T)\,, \tag{1}$$

where the density ρ, the specific heat c_p, and the conductivity κ take the value corresponding to each material of every layer of the envelope.

This equation is closed with boundary conditions for the external and internal surfaces of the roof that are given by the energy balance equation corresponding to each surface, as is explained in Section 2.2.2.

2.2.2. Energy Balance at the Roof Surfaces

For the external surface of the roof, the energy balance is given by:

$$\kappa \frac{\partial T}{\partial \vec{n}} + q_{c,ext} + q^{SW} + q^{LW} = 0\,, \tag{2}$$

where $q_{c,ext}$ is the intensity of the convective heat flux between the surface and the air flow that is given by:

$$q_{c,ext} = h_{c,ext}(T_a - T), \quad (W/m^2),$$

with T_a the outdoor air dry-bulb temperature, T the exterior roof surface temperature, $\vec{n}$ the outward normal vector to the exterior roof surface, and $h_{c,ext}$ the convective heat transfer coefficient described in Section 2.2.4. Finally, q^{SW} and q^{LW} are respectively the intensity of radiative flux of solar origin and the intensity of the balance of thermal long-wave radiation on the surfaces whose calculation is explained in Section 2.2.3.

For the internal surface of the roof the energy balance is given by:

$$\kappa \frac{\partial T}{\partial \vec{n}} + q_{cr,int} = 0\,, \tag{3}$$

where now, $\vec{n}$ is the outward normal vector to the interior roof surface, T is the interior roof surface temperature, and $q_{cr,int}$ is the intensity of the combined convective-radiative heat transfer between the internal roof surfaces and the interior temperature. This is given by:

$$q_{cr,int} = h_{conv,rad}(T_{room} - T), \quad (W/m^2), \tag{4}$$

where $h_{conv,rad}$ is the combined convective-radiative heat transfer coefficient explained in Section 2.2.4 and T_{room} is the interior air temperature.

2.2.3. Solar and Long-Wave Radiative Flux

For the external surface of a roof, the absorbed solar radiative flux is given by:

$$q^{SW} = \alpha^{SW} \cdot \left(I_b^{SW} \cdot cos(\theta) \cdot \frac{S_s}{S_{roof}} + I_{sd} \cdot F_{rs} + I_{gd} \cdot F_{rg} + I_{rn} \cdot F_{rn} \right), \quad (W/m^2), \tag{5}$$

where α^{SW} is the solar absorptance of the external roof surface, θ is the angle of incidence on the roof of the sun's rays, I_b^{SW} is the intensity of the beam solar radiation, S_s and S_{roof} are the sunlit and the entire roof areas, respectively, and I_{sd} and I_{gd} are the intensity of the diffuse radiation reflected by the sky and the ground, respectively, F_{rs} being the view factor between the roof and the sky and F_{rg} the view factor between the roof and the ground. Finally, I_{rn} is the intensity of the reflected radiation by the surrounding buildings, and F_{rn} is the the view factor between the roof and such buildings.

In the absence of buildings or shading elements higher than the roof under consideration, F_{rs} and F_{rg} are given by:

$$F_{rs} = \frac{1 + cos(\varphi)}{2}, \qquad F_{rg} = \frac{1 - cos(\varphi)}{2}$$

φ being the angle between the roof plane and the horizontal plane. For an unshaded flat roof, Expression (5) becomes:

$$q^{SW} = \alpha^{SW} \cdot I_H^{SW}, \quad (W/m^2), \tag{6}$$

where I_H^{SW} is the global horizontal solar radiation intensity given by $I_H^{SW} = I_b^{SW} \cdot cos(\theta) + I_{sd}$.

The long-wave radiation balance for the external roof surface is calculated as:

$$q^{LW} = Q_{sky}^{LW} - Q_w^{LW}$$

where Q_w^{LW} is the intensity of the long-wave radiation heat emitted by the external roof surface and Q_{sky}^{LW} is the sky downwelling long-wave radiation.

Q_w^{LW} is calculated using the law of Stefan–Boltzmann:

$$Q_w^{LW} = \epsilon \sigma T^4 \tag{7}$$

ϵ being the surface emissivity, T the temperature in Kelvin degrees of the surface, and $\sigma = 5.67 \cdot 10^{-8}$ $[\mathrm{W/m^2 \cdot K^4}]$ the constant of Stefan–Boltzmann.

The sky downwelling long-wave radiation Q_{sky}^{LW} depends on several factors, but the most significant ones are outdoor temperature, the relative humidity of the environment, and cloud cover. Essentially, clouds absorb outgoing IR radiation and emit thermal IR radiation to a temperature higher than emitted by a clear sky. Thus, a cloudy day thermal downwelling sky irradiance can increase over 34% regarding the sky irradiance of a clear sky. Q_{sky}^{LW} can be computed as:

$$Q_{sky}^{LW} = \epsilon_{sky} \sigma T_a^4, \tag{8}$$

where ϵ_{sky} is the sky emissivity. Walton [32] and Clark et al. [33] estimated that ϵ_{sky} can be calculated as:

$$\epsilon_{sky} = (0.787 + 0.764 \ln(\frac{T_{dp}}{273}))(1 + \frac{224}{10^4} n - \frac{35}{10^4} n^2 + \frac{28}{10^5} n^3)$$

where T_{dp} is the absolute dew point temperature and n is the opaque sky cover in tenths. This is the correlation used in this work.

2.2.4. Convective Heat Transfer Coefficients

Suitable Convective Heat Transfer Coefficients (CHTC) for external building surfaces, $h_{c,ext}$, are essential in order to calculate accurately heat transfers between the roof surface and the ambiance air. However, while for vertical surfaces, there is a large number of correlations, for roofs, they are much scarcer. As stated by Mirsadeghi et al. [34], convective heat transfer calculations for roofs represent some of the most complex problems in wind flow around buildings due to the variety in their geometry and the complex flow patterns in the separated regions above the roofs.

In this work, the correlation used for the external surface of roof is $h_{c,ext} = 8.18 + 2.28\, V_R$ $(\mathrm{W/m^2K})$, which was proposed by Hagishima and Tanimoto [35] based on experiments carried out on a roof. Here, V_R is the wind speed above the roof in m/s.

To calculate the heat exchange by convection and radiation between the internal roof surface and the interior of the building, a combined convective-radiative transfer coefficient given by $h_{conv,rad} = 8.3$ $(\mathrm{W/m^2K})$ is used as recommended by ASHRAE [36]. This coefficient is often used in heat transfer calculation for buildings' interiors [37].

2.3. Aging Effect on the Cool Roof Absorptivity

This paper aims to carry out a long-term assessment of the energy behavior of the cool roofs in order to perform an LCA for a lifetime period of 20 years according to the service time of the roof coating. For such a long period, it is necessary to take into account the loss of the reflective properties of the roof coating over time due to its own aging or to the action of environmental agents as rain, dust, air particles, moisture, and sun.

According to [22], the aging of a paint depends on the characteristics of the paint itself (porosity, glass transition temperatures, water retention capacity). It also depends on the material on which the paint is applied (roughness) and on a number of environmental factors to which the paint is exposed. Mastrapostoli et al. [38], analyzing the weatherization of cool roofs in two Athenian schools, showed that the solar reflectance, after four years, decreased by around 25%. Xue et al. (2015) [39], by making use of a white roof coating based on styrene acrylate copolymer and cement, showed that after 400 h of artificial accelerated weathering, solar reflectance experienced a decrease of 11%.

In [40], it was found from a field survey that for all reflective roofing types, about 95% of aging occurred during the first two years, and 98% occurred within the first three years of installation. The conclusions for unwashed white roof coatings applied to a variety of substrates suggested a loss of solar initial reflectivity of about 20–25%, taking place in the first few months to one year, with little change beyond that and generally little variation by substrate.

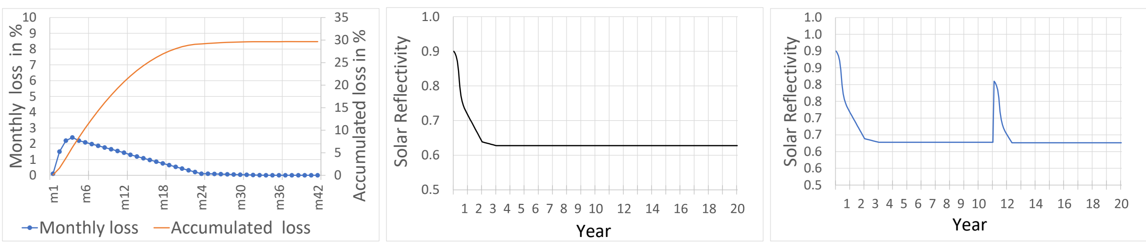
According to Bretz and Akbary [41], most of the decrease in solar reflectivity occurred in the first year, possibly in the first few months. Then, values tended to stabilize. Eilert [42] also proved that the reduction in the solar reflectivity of white roofs was in the order of 10–30%, with most of the reduction occurring in the first year. In the field survey [40], it was concluded that the energy calculations should be based on at least one year aged reflectivity values, which were typically 75–80% of the initial values. The same was concluded in [22]. In this study, the results obtained from in-field measurements pointed to a reduction of the solar reflectance between 19 and 25% for different cool paints. In the same work, it was also observed that the aging of the cool coating layer did not significantly affect its thermal reflectivity.

On the other hand, in-field measurements [40,41] found that the original values for the reflectivity could be restored up to 90–100% by a periodic power washing. Nevertheless, the author of this field survey concluded that washing of cool coated roof surfaces as a maintenance measure did not constitute a cost-effective means of retaining or restoring solar-reflectance values, especially considering that most solar reflectance loss would reoccur in three to six months. While washing could usually restore most of the solar reflectivity, at least during the first several years of aging, the effects were short lived (typically three to six months) and yielded limited economic payback.

For the calculation of energy flows through the roofs, four scenarios for the cool coating were considered: roofs without the aging effect, roofs with the aging effect, but without any maintenance, roofs with the aging effect and a wash maintenance after a decade, and finally, aged roofs with quinquennial wash maintenance. Taking into account the social nature of the buildings in which the roof refurbishment was carried out, considering an annual roof washing seemed unlikely, it being more realistic to consider a maintenance wash with quinquennial or decennial periodicity or no maintenance.

Based on what was supported by most of the studies reviewed, the aging pattern considered in the present work for the cool roof coating was the following: throughout the first year, a loss of solar reflectivity equal to 20% of its initial value, concentrated mostly in the first months of the year, and a loss equal to 8.5% in the second year. For the third year, a loss equal to 0.9% was assumed. Then, the decrease in reflectance tended to become stabilized [41], until reaching a total loss of 30% for the whole life cycle span. This way, about 95% of the aging happened during the first two years, and 98% occurred within the first three years after the installation, as is stated in [40]. For the considered case of a wash a decade after the installation, the related literature assumed the solar reflectivity to be restored to 90% of the initial value. Afterwards, the same pattern as that taking place after the initial application of the cool coating was considered.

In Figure 1a, the monthly and accumulated percentages of solar reflectivity loss are shown, according to the aforementioned aging patterns. The evolution of the solar reflectivity for the aged case without maintenance and for the aged case with decennial washing are shown respectively in Figure 1b,c for a roof coating with an initial reflectivity equal to 0.9.



(**a**) (**b**) (**c**)

Figure 1. Monthly and accumulated percentage of solar reflectivity loss (**a**). Evolution of the solar reflectivity for the aged case (**b**) and for the aged case with decennial washing (**c**).

2.4. Case Buildings

For our study, a representative building of the social park housing built in Seville before 1979 was considered. This building belonged to the promotion of social housing called El Plantinar built in Seville in the 1960s. The constructive typology of this promotion was typical of social housing in this decade.

The roofs were flat type, and as can be seen in Figures 2 and 3, the promotion was made up of buildings of the same height, while there were no close buildings of higher height that could cast shadows over them. Therefore, the flux of the solar radiation incident on the roofs is given by Expression (6).

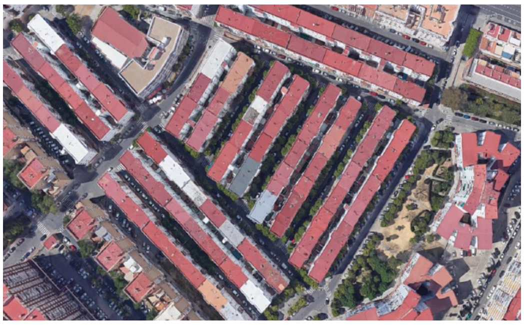


Figure 2. El Plantinar: aerial view.

Figure 3. El Plantinar: aerial view.

The roof configuration is described in Table 1, where dimensioning and thermophysical characteristics of the various components of the roofs are shown. The values shown in this table were obtained from [43,44].

The outer surface of the roof was considered covered by a layer of bituminous paint. Then, two absorptivity solar radiation coefficients of 0.8 and 0.9 were studied according to the usual values of the absorptivity for this kind of coating. These values represented the benchmark cases to be compared with the cool roofs.

In order to transform the roof to a cool roof, the application of a white elastomer layer on the surface of the outer layer of the roof was selected. Taking into account the wide variety of existing commercial cool paints and seeking to find their energy and economic performance in a broader way, cool roof coatings with absorptivities equal to 0.1, 0.2, 0.3, and 0.4, which could be easily found in commercial suppliers, were studied.

In Figure 4, the climatic chart of Seville is shown. As can be noted, winter could be characterized as mild and summers as hot and dry with high levels of solar radiation. Finally, autumns and springs were characterized by rainfall and moderate temperatures. According to the data from the Spanish State Meteorological Agency [45], the average annual temperature was 19.2 °C, with maximum average temperatures up to 40 °C in the months of July and August and a minimum average of 5.7 °C in January. The normal incident solar radiation value had a maximum average daily value of 8.3 kWh/m^2 in July and a minimum daily average value of 2.3 kWh/m^2 in December. In accordance with these characteristics, the climate of the area was classified as Mediterranean Csa according to the Köppen–Geiger climate classification.

Table 1. Thermophysical characteristics of the roof.

Layer	Description	Thickness (m)	Density (kg/m^3)	Specific Heat (J/kgK)	Conductivity (W/mK)
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	Concrete vault	0.3	1330	1000	1.32
8 (Int.)	Gypsum plaster	0.01	1000	1000	0.32

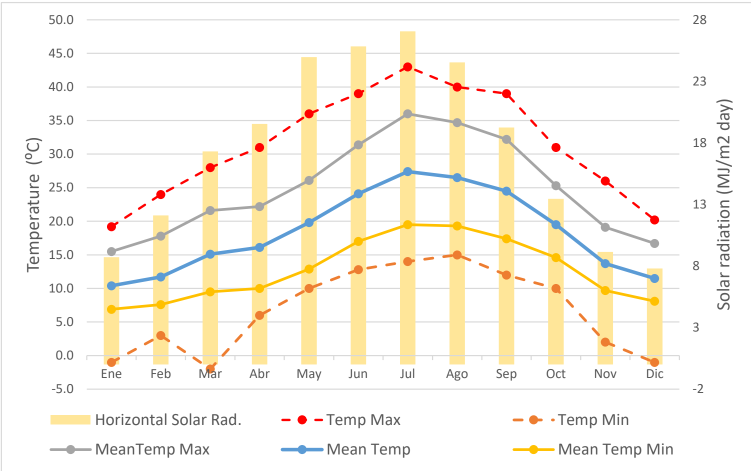


Figure 4. Climatic chart of Seville.

2.5. Numerical Resolution

Equation (1) for the heat transfer through the roof was solved by using a one-dimensional finite difference approximation in space and a semi-implicit Euler method for time. The entire computation process was executed developing a code based on the described numerical method using the open source FreeFem++ software [46]. For the temperature on the solid surfaces, the border conditions were chosen from the energy balance equations as described in Section 2.2.2.

In order to ensure the reliability of the proposed numerical method, it was first validated through an inter-model comparison with the Energy Plus software [47]. This was made by considering short time intervals for the calculation, typically months, due to the fact that Energy Plus does not implement time dependent absorptance since it is only able to deal with constant values of solar absorptance. This feature was implemented in our numerical model by means of allowing the simulation of the aging effect on cool roof absorptance in long time intervals, typically decades, as was done in our LCA calculations. Likewise, from a purely numerical point of view, the method was checked through the analytical calculation of the evolution of the temperatures on the nodes used for the difference finite method calculations by using a low number of nodes for the discretization of the roof [48].

The general calculation process had the following steps:

- Phase I. Preprocess:

I.A Input of geometry and materials' data: in this phase, the geometry of the roof was entered and stored, as well as the data of the materials involved in the simulations.

I.B Input of meteorological data: wind speed, ambient air temperature, ambient relative humidity, and solar radiation were stored. These values could be taken from standard weather files as the Energy Plus Weather (EPW) files, or from a local meteorological station, or derived from some model.

I.C The downwelling long-wave radiation incident on the roof was calculated for every time considered in computations. These calculations were performed once and could be incorporated as data in the simulation process.

- Phase II. Time iterations:

  For every time step, heat transfer coefficients and radiative heat exchange were upgraded, and the border conditions given by surface energy balances on every surface, Equations (2) and (3), were updated. Finally, the heat transfer Equation (1) for the roof was solved at the current time.

For the interior zone under the roof, we considered a test zone inspired by [28,49,50] assuming the envelope was adiabatic except for the roof. The thermal behavior of the roof depended on the operating mode of the conditioning system. Different modes can be found in the literature: continuous air-conditioning [27,28,51–53], intermittent air-conditioning with a fixed indoor set-point temperature [54], and no air-conditioning with fluctuating indoor temperature [55].

In order to evaluate the energy behavior of the roof and its impact on the energy loads, we assumed that the ambient interior temperature was kept constant for every season. We assumed a continuous mode of the conditioning system with an indoor set-point temperature for the cooling season set at 24 °C, for the heating season set at 20 ° C, and for the intermediate seasons set at 22.5 °C. These values were selected by taking into consideration the comfort temperature intervals established in the Spanish regulation of thermal installations in buildings (RITE) [56]. On the other hand, these values were used in previous research on cool roofs under climatic conditions similar to those of the present study [28].

3. Life Cycle Cost Analysis

An accurate approach to the economics of the cool roof is the assessment of its cost-effectiveness through an LCA that takes into account future costs [57].

This method allows a comparison of future costs with today's costs while evaluating throughout the life cycle period the savings obtained when cool roofs are used.

To make the life cycle cost analysis, all anticipated costs were calculated and discounted to their present worth. The usual procedure is to compute the costs for each future year taking into account the future value of the variables that generate the costs and then to discount each annual cost to its present worth. Finally, the sum of all the present values constituted the life cycle cost.

When the life cycle cost was determined for each of the roofing systems under consideration, including different cool and non-cool roof options and different scenarios for aging, the cost-effectiveness of each system was appraised by its life cycle costs; the lowest was the life cycle cost, the most cost effective was the system, and equivalently, the systems with highest life cycle savings were selected as the most cost effective.

3.1. Methodology

For the LCA, we considered a lifetime of $n = 20$ years, that is the average life service of the considered white reflective coating [58]. Then, the life cycle cost and saving together with the payback period for each of the considered cool roof scenarios were determined. In this analysis, the costs of energy, the performance of the equipment used for air-conditioning, the initial cost of application of the reflective coating, and the maintenance costs derived from the power washing of the cool roofs were considered, as well as the economic variables that drove the economic process: the increase of energy costs i and the monetary discount rate d.

In the LCA analysis, the method P1-P2introduced in [57] was used with some small differences due to the dynamic character of the yearly energy operating costs induced by the aging and maintenance of the cool roofs. To determine 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:

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

Then, if $P_{e,C}$ and $P_{e,H}$ are the current prices of energy for cooling and heating, respectively, and if i is the inflation rate for energy costs, the present worth of any future energy payment $C_e(k)$ in the period k is given [57] by:

$$PW_k(C_e(k)) = C_e(k)/(1+d)^k$$

where:

$$C_e(k) = \left(\frac{Q_c(k)\,\times\,P_{e,c}}{SEER\,\times\,(3.6\times10^6)} + \frac{Q_h(k)\,\times\,P_{e,h}}{SCOP\,\times\,(3.6\times10^6)} \right)(1+i)^{k-1} \tag{9}$$

where SEER is the Seasonal Energy Efficiency Ratio and SCOP is the Seasonal Coefficient Of Performance of the equipment used for conditioning. Equation (9) takes into account the fact that the energy loads $Q_c(k)$ and $Q_h(k)$ for the cool roofs varied annually because of the aging effect and the maintenance to which the cool coating was subjected. In the calculation of $C_e(k)$, it was considered that the energy used for cooling was always electricity, but for heating, the costs were evaluated both considering the use of electricity and gas.

Likewise, if i_M is the inflation rate for the costs of maintenance, the present worth of any future maintenance payment $C_M(k)$ in the period k is given by:

$$PW_k(C_M(k)) = C_M(k)/(1+d)^k \;=\; \delta(k)\,C_M(1+i_M)^{k-1}/(1+d)^k$$

where $\delta(k)$ is equal to 1 if the maintenance is done in year k or equal to 0 if not and C_M is the current price of maintenance per unit area of roof surface.

Then, the present worth of the life cycle total cost per unit area of the roof surface is given by:

$$C_t = C_e + C_M + C_I$$

where C_e and C_M are the present worth of energy and maintenance life cycle total cost, respectively, calculated as:

$$C_e = \sum_{k=1}^{n} PW_k(C_e(k)) \quad \text{and} \quad C_M = \sum_{k=1}^{n} PW_k(C_M(k))\,,$$

and C_I is the cost of the initial investment of installing the cool roof coating.

When compared with the initial reference roof, due to the refurbishment, there will be annual operational changes in terms of energy together with the corresponding changes in economic terms related mainly to the energy costs. In order to calculate the difference between the use of the cool roofs and the reference case, we calculated the Net Savings (NS) for the whole life cycle period through:

$$NS \;=\; \sum_{k=1}^{n} \left[PW_k(C_e^{(ref)}(k)) - PW_k(C_e(k)) \right] - C_M - C_I\,. \tag{10}$$

Here, $PW_k(C_e^{(ref)}(k))$ is the present worth value of the energy costs for the reference case in the period k given by:

$$PW_k(C_e^{(ref)}(k)) = C_e^{(ref)}(k)/(1+d)^k,$$

being:

$$C_e^{(ref)}(k) = \left(\frac{Q_c^{(ref)}(k)\,\times\,P_{e,c}}{SEER\,\times\,(3.6\times10^6)} + \frac{Q_h^{(ref)}(k)\,\times\,P_{e,h}}{SCOP\,\times\,(3.6\times10^6)} \right)(1+i)^{k-1} \tag{11}$$

where now $Q_c^{(ref)}(k)$ and $Q_h^{(ref)}(k)$ are the cooling and heating loads, respectively, for the reference roofs in the time period k.

Then, $PW_k(C_e^{(ref)}(k)) - PW_k(C_e(k))$ is the difference in the period k between the energy costs for the reference roof and the cool roof under analysis. A positive value of NS means that the use of the cool coating produces savings with respect to the reference case. It is worth highlighting the fact that energy consumption varies annually due to the aging effect, and therefore, Expression (10) cannot be reduced to a single analytical expression.

The Payback Period (PB) is the time horizon t for which the value of net savings is equal to zero [59]. Because the series coefficients in (10) are variable for the time step k, the value t giving the payback period is obtained through the computations of the net savings accumulated for every horizon k_0:

$$NS(k_0) = \sum_{k=1}^{k_0} \left[PW_k(C_e^{(ref)}(k)) - PW_k(C_e(k)) \right] - C_M - C_I\,. \tag{12}$$

Then, if $NS(k_0) < 0$ and $NS(k_0+1) > 0$, the value of the payback period t is calculated through the expression:

$$t = \frac{-NS(k_0)}{NS(k_0+1) - NS(k_0)} + k_0\,. \tag{13}$$

The value of t provided by (13) is consistent with the usual value found in the literature [28–57] when energy consumption is assumed to be constant for all years.

3.2. Economic Indicators

The variables considered to perform the economic calculations involved in the LCA are listed in Table 2.

Table 2. Economic variables used in the LCA.

Variable	Value	
Cool paint application	9.45	€/m^2
Washing cost	1.63	€/m^2
Electricity cost	0.2403	kWh
Gas cost	0.0736	kWh
Energy inflation rate	0%, 3%, 6%	
Discount rate	0.5%, 1.5%, 3%	
Lifetime	20	years

The costs of the cool paint application and its maintenance were taken from [58]. The electricity and natural gas prices were the prices in Spain (including taxes) for household consumers [60]. Following the approach of [61], three possible values for the energy inflation and the discount rates were considered, as shown in Table 2. Finally, the maintenance discount rate i_M was taken equal to d under the supposition that the evolutions of both indexes were close to each other.

For the conditioning equipment, we considered that cooling was always done by the air-conditioning machinery that used electricity as the only energy source. For heating, the following cases were considered:

- Heating by natural gas.
- Heating by electricity radiators.
- Heating by air (heat pumps).

Since the purchasing power of the inhabitants of these homes was not high, it was considered that the air-conditioning devices were mid-range with an A++ energy rating according to the European regulations, under the assumption that these devices were usually less expensive than those with the energy certification A+++. The efficiency values of the conditioning equipment are shown in Table 3.

Table 3. Conditioning equipment efficiency. SEER, Seasonal Energy Efficiency Ratio; SCOP, Seasonal Coefficient Of Performance.

Device	Efficiency		
Cooling pump	SEER	=	7.3
Heating pump	SCOP	=	4.85
Gas natural heating	η_s	=	0.8
Electrical radiator heating	η_s	=	1

The values shown in Table 3 for the pump were the means of the values established in the EU Regulation 626/2011 [62] for an air-conditioning equipment labeled A++.

4. Results

In this section, the results from the energy and economic LCA analysis are presented.

4.1. Energy Results

4.1.1. Cool Roof Energy Performance

In this section, an analysis of the energy performance of the cool roof is done by using the introduced numerical method applied to the case study with the non-insulated roof described in Section 2.4. In the first stage, the energy performance of the roof was assessed with solar reflectivity covering a range from 0.1 to 0.9. Then, transmission loads per unit area of the roof surface were calculated for the whole climatic year.

In Figure 5, the behavior of the temperatures over a week that covered the last days of July and the first ones of August is shown for a reference roof and a cool roof. For the reference roof, a solar absorptivity equal to 0.9 and a thermal emissivity of 0.85 were considered, while for the cool roof, a solar absorptivity equal to 0.1 and a thermal emissivity of 0.9 were assumed.

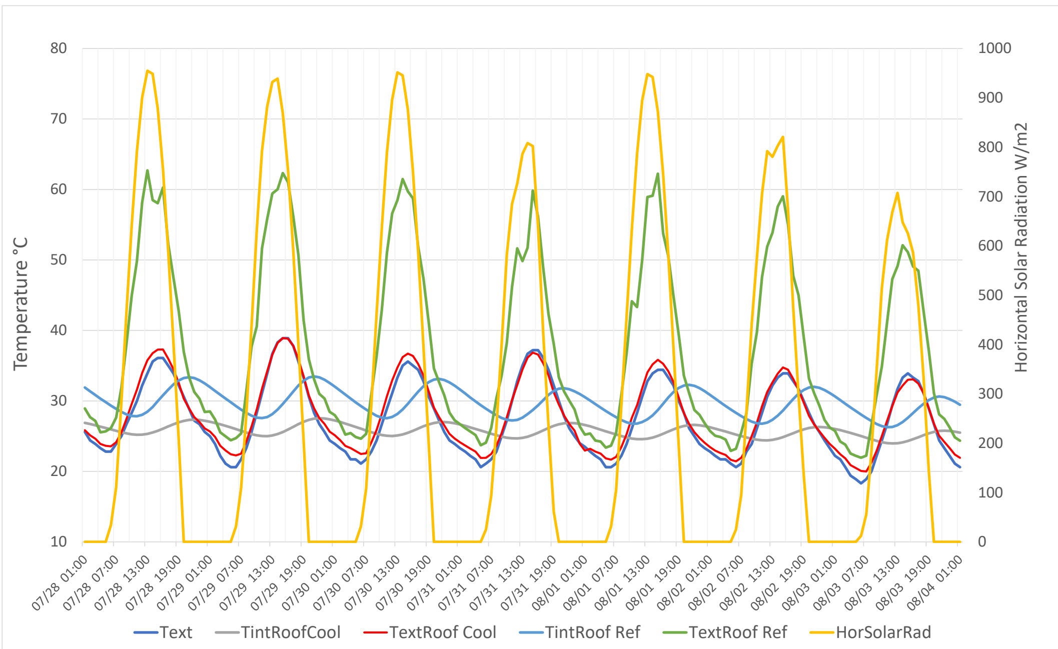


Figure 5. Temperatures for the reference and cool roofs during a week of summer.

In this figure, the typical behavior of the cool roof is observed. Most of the time, the external layer of the cool roof had a temperature close to the ambient temperature, whereas that of the reference roof had temperatures much higher, especially in the central hours of the day, where the solar irradiation was more intense. At night, there was a significant drop in surface temperatures caused by the absence of solar irradiation and by the cooling caused by the radiative exchange with the sky vault. However, the thermal energy accumulated in the mass of the roofs made the temperatures of the surface layers in general higher than the environmental ones, a fact that was much more evident for the reference roof. Moreover, the daily fluctuations of the temperatures were much smaller for the cool roof. This way, cool roofs were better protected against thermal fatigue. This resulted in a longer service life for the roof.

Another important fact was the remarkable difference observed between the temperatures of the interior surfaces of the two types of roofs. Firstly, the temperature of the internal surface of the reference roof was several degrees higher than that of the cool roof, but it also had much stronger oscillations. Both events strongly affected the energy consumption to achieve interior comfort conditions and the sensation of thermal stress.

In Figure 6, the monthly heat flux through the roof is shown, considering inwards heat flux as positive and outwards heat flux as negative. It can be seen that the effect of low absorptivity values was very pronounced in summer. Thus, for an absorptivity of 0.1, the cooling load was significant only for the months of July and August. On the other hand, this low absorptivity value introduced a considerable penalty in wintertime, which resulted in a higher value of the heating load. This combined effect was the basis for for the estimation of the energy savings achieved by the use of cool roofs. In general, it was observed that as the absorptivity value increased, a gradual increase occurred of the cooling load in the warm season and a decrease of the heating load in the heating season.

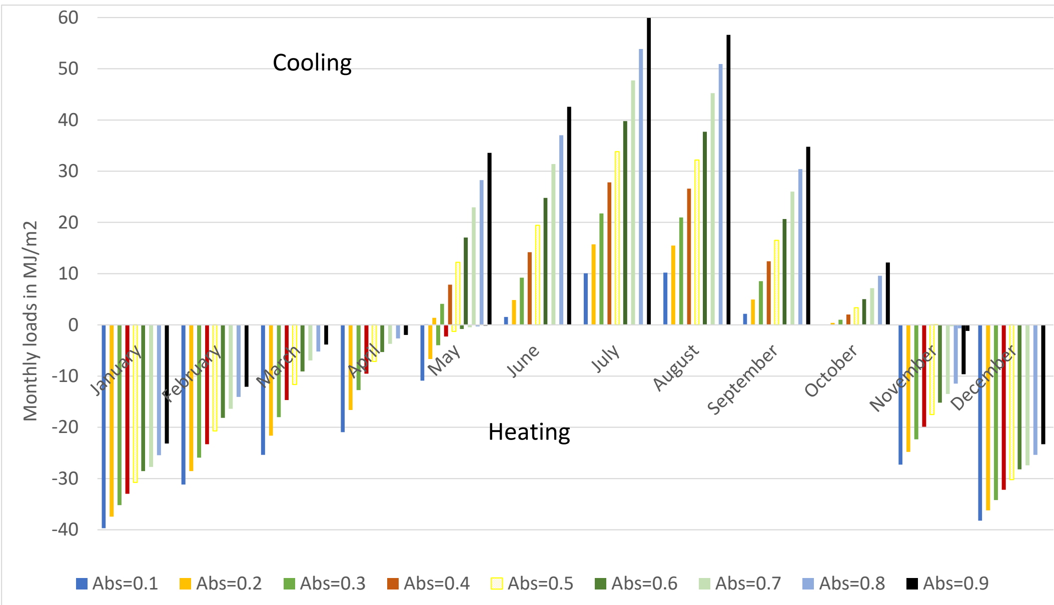


Figure 6. Effect of the solar absorptivity on monthly heat flux through the roof.

Figure 7 shows for the different values of the absorptivity the annual transmission loads per unit area of the roof surface for the case study. From this graph, it can be concluded that the lowest energy consumption values were obtained for the lowest values of solar absorptivity. Specifically, for the values 0.1 and 0.2 of the absorptivity, while the values of total consumption were practically the same, the difference lied in the values of loads for heating and cooling. Such values showed a notable difference according to what was said before: higher levels of solar reflectivity corresponded to lower values of cooling load and higher values of heating load.

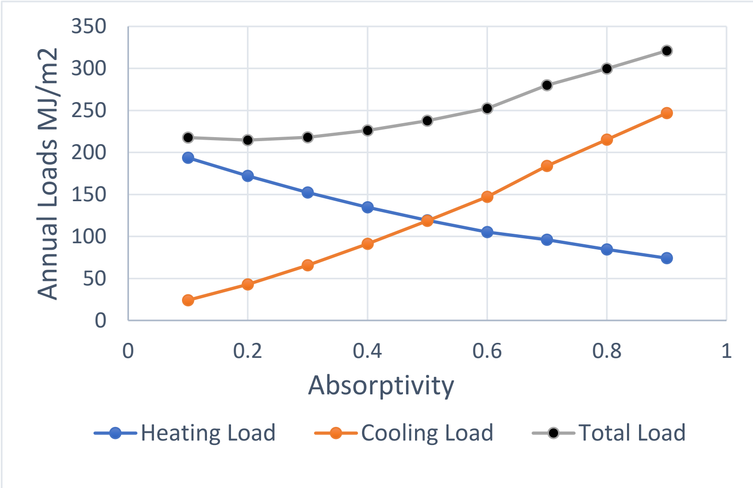
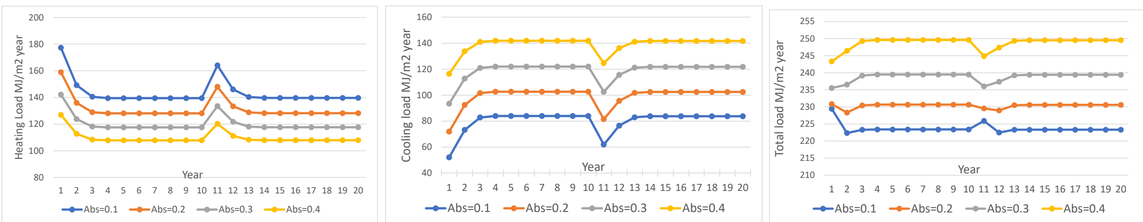


Figure 7. Effect of the solar absorptivity on annual heat flux through the roof.

4.1.2. Aging Effect on the Energy Loads

In Figure 8a–c, the evolutions of the heating, cooling, and total loads are shown for the aged case with decennial wash maintenance for the four absorptivity scenarios studied. It can be observed that the progressive loss of solar reflectivity in the first years produced an increase of the cooling loads and a decrease of the heating for all the cases. After four years, the loads tended to become constant until the decennial wash maintenance was done. At this moment, the initial behavior for the loads was repeated, although a variation of the initial values of the loads was observed according to the fact that the wash recovered only 90% of the initial reflectivity. For the total loads, it was observed that for the value of the absorptivity equal to 0.1, the aging effect produced a decay of the total load. This was due to the fact that, in spite of the cooling load increasing during the summer, such an increase was advantageously offset by the reduction of the winter penalty.

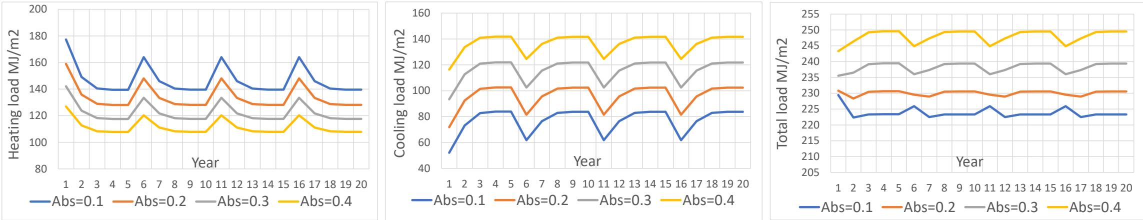


(**a**) (**b**) (**c**)

Figure 8. Aged case with decennial washing. Yearly evolutions of the: heating loads (**a**), cooling loads (**b**), and total load (**c**).

For the value of the absorptivity equal to 0.2, the aging effect also produced an initial decrease in the second year for the total load, although it rapidly recovered the initial load values. However, after the ten year maintenance, a somewhat longer further decrease in total loads than at the beginning of the cycle was observed. For the higher absorptivity values, that is 0.3 and 0.4, it was observed that the aging effect, both initially and after the ten year maintenance, resulted in an increase in total loads since in these cases, the increases in cooling loads were not compensated by the reductions in heating loads.

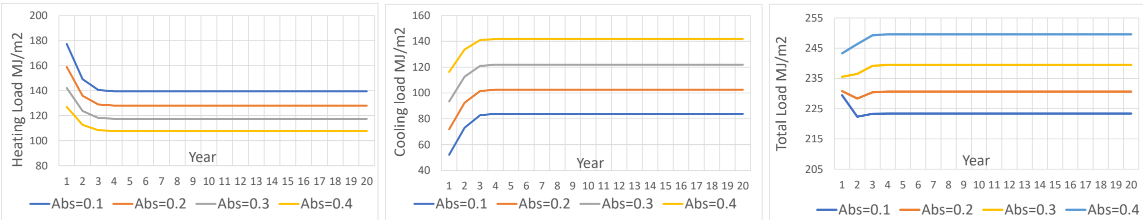
In Figure 9a–c, the evolutions of the heating, cooling, and total loads are shown for the aged case with a quinquennial washing. In these figures, the same patterns as for the decennial washing can be observed although with a five year periodicity, that is, an increase of the heating loads and a decrease of the cooling loads in the first years after every washing together with an initial decrease of the total loads after washing for all the roofs' absorptivities except for the case of the roof absorptivity equal to 0.1, where the aging effect gave rise to the same decrease of the total roof as that of the case of the decennial maintenance.



(**a**) (**b**) (**c**)

Figure 9. Aged case with quinquennial washing. Yearly evolutions of the: heating loads (**a**), cooling loads (**b**), and total loads (**c**).

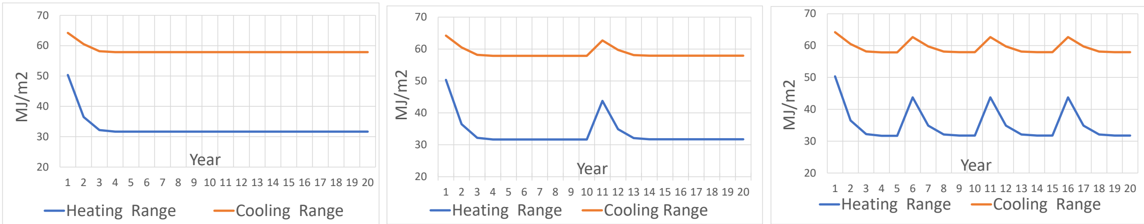
Finally, in Figure 10a–c, the evolutions of the heating, cooling, and total loads are shown for the aged case without any maintenance along the entire LCA lifetime period. In this case, the aging effect reproduced the initial pattern observed in the previous cases, that is a decrease of the heating loads and an increase of the cooling loads for all the cool roof scenarios, a decrease of the total loads for the case of absorptivity equal to 0.1 due to the increase of the cooling load being offset by a decrease in the heating load, an initial decrease and a later recovery of the initial load values for the absorptivity equal to 0.2, and finally, for the remaining cases, a net increase of the total loads for the first years, which remained stabilize from the fourth year until the end of the lifetime period.



(**a**) (**b**) (**c**)

Figure 10. Aged case without maintenance. Yearly evolutions of the: heating loads (**a**), cooling loads (**b**), and total loads (**c**).

In Figure 11, the range of variation of the loads related to the range of variation of the roof absorptivities for the three studied aged cases is shown. The heating variation range curves show the difference between the heating load for the absorptivity equal to 0.1 minus the heating load for an absorptivity equal to 0.4, and the cooling range curve shows the difference between the cooling load for the roof with an absorptivity equal to 0.4 minus the cooling load for an absorptivity equal to 0.1. As can be seen, for all the cases, the effect of the change in absorptivity values was greater on the cooling loads than on the heating ones. In fact, initially, this range of variation was about 65 MJ/m^2 year for the cooling range and of 50 MJ/m^2 year, that is a difference of 15 MJ/m^2 year. However, once the aged effect stabilized the solar absorption values, the difference was close to 30 MJ/m^2 year , that is almost double, and the same pattern was observed after the washing maintenance. In short, the effect of changes in absorptivity produced a noticeably greater impact on the cooling loads than on the heating ones.



(**a**) (**b**) (**c**)

Figure 11. Yearly range variation of the heating and cooling loads for the aged case: without maintenance wash (**a**), with decennial wash (**b**), and with quinquennial wash (**c**).

The total loads in GJ/m^2 along the entire lifetime period for the different cool roof and maintenance scenarios are shown in Figure 12 together with the two reference roofs without retrofitting. It can be noted that for all cool roof cases and scenarios, the total loads were lower than those of the reference roofs. Moreover, it was also observed that the lower the absorptivity, the lower was the total load. Regarding the maintenance regime, no significant differences were found among the total loads, except for the unrealistic case of no aged roof that was only included as an indicator of the need to include the aging effect.

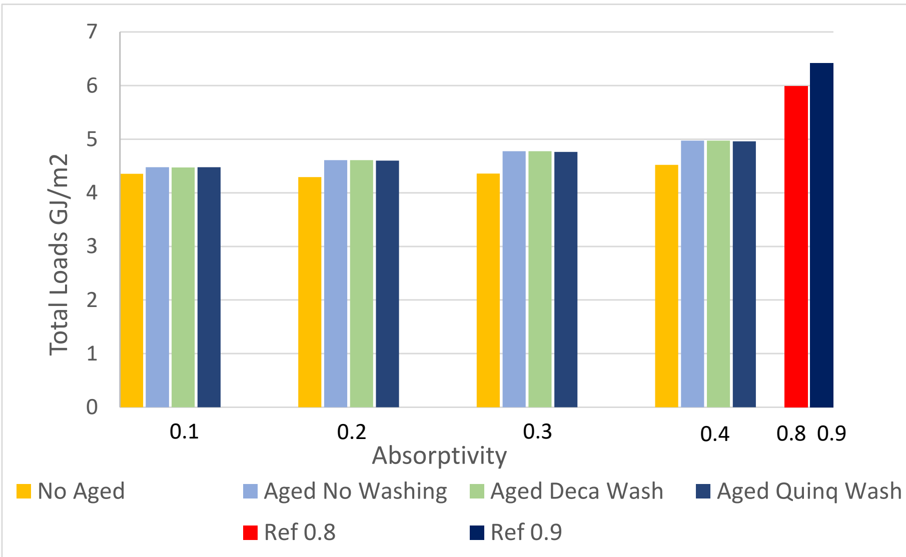
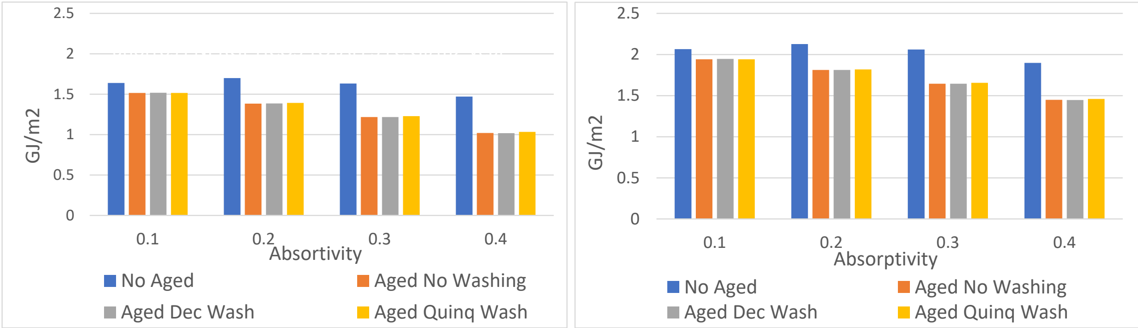


Figure 12. Total loads for the entire LC period.

In Figure 13a,b and Table 4, the total load savings are shown for the entire LC period. In these, it can be observed that the decreases of the total load for the reference roof with $abs_{ref} = 0.9$ were higher than for the reference roof with $abs_{ref} = 0.8$ according to the idea that for warm climates' cool coatings were more efficient in order to reduce the loads the higher was the absorptivity of the roof retrofitted with the cool coating. Likewise, the growing effect on the total loads' reduction that resulted from the decrease in absorptivity was observed. On the other hand, no significant differences were appreciated among the different maintenance scenarios, as stated previously.



(**a**) (**b**)

Figure 13. Life cycle period total load decreases (GJ/m^2) for: roof reference absorptivity = 0.8 (**a**); roof reference absorptivity = 0.9 (**b**).

Table 4. Life cycle period total load decreases in GJ/m^2.

	Reference Absorp. = 0.8				Reference Absorp. = 0.9			
Cool Roof Absorptivity	No Aged	Aged No Wash	Aged Dec.Wash	Aged Quinq.Wash	No Aged	Aged No Wash	Aged Dec. Wash	Aged Quinq. Wash
0.1	1.638	1.515	1.519	1.515	2.065	1.942	1.946	1.942
0.2	1.699	1.384	1.385	1.391	2.126	1.811	1.812	1.818
0.3	1.632	1.217	1.216	1.228	2.060	1.644	1.644	1.655
0.4	1.471	1.020	1.018	1.032	1.898	1.447	1.445	1.460

4.2. LCA Economic Results

In this section, the LCA results of the cool roof refurbishment are presented using the NS and PB as performance indicators. The net savings and payback periods owing to refurbishment investment with the four cool roofs' absorptivities $abs_{cool} = 0.1, 0.2, 0.3, 0.4$ when compared with the reference roofs with absorptivities $abs_{ref} = 0.8, 0.9$ were analyzed under the economic framework described in Section 3 and for all the aging scenarios described in Section 2.3. Positive values for NS mean real savings, while negative values imply a higher LCA cost for the cool roof and, therefore, no real savings.

Two cases were taken into account for the LCA:

- The cool retrofit installation was not necessarily required, and the decision about its installation was driven by energy savings considerations. In this case, the installation costs were considered in full.
- The roof needed renovation, and the installation of a cool roof was opted for instead of implementing a classic system, which in our study was considered to be made with bituminous insulating paint. In this case, the installation costs were considered marginal, since they were computed as the difference between the cost of installation of the cool roof minus the installation cost for the bituminous paint.

In Tables 5 and 6, the maximum total cost savings are summarized for the whole life cycle period of time. Details about these results are analyzed in the next sections.

Table 5. Full costs: life cycle period maximum total savings in €/m^2.

	Reference Absorp. = 0.8				Reference Absorp. = 0.9			
Cool Roof Absorptivity	No Aged	Aged No Wash	Aged Dec. Wash	Aged Quinq. Wash	No Aged	Aged No Wash	Aged Dec. Wash	Aged Quinq. Wash
0.1	−0.77	5.09	3.23	−0.79	4.46	10.32	8.47	4.43
0.2	3.76	4.76	3.05	−0.71	9.00	9.99	8.28	4.51
0.3	14.61	3.96	2.29	−1.31	11.13	9.19	7.52	3.92
0.4	6.15	2.52	0.87	−2.62	11.39	7.76	6.11	2.61

Table 6. Marginal costs: life cycle period maximum total savings in €/m^2.

Cool Roof Absorptivity	Reference Absorp. = 0.8 No Aged	Aged No Wash	Aged Dec. Wash	Aged Quinq. Wash	Reference Absorp. = 0.9 No Aged	Aged No Wash	Aged Dec. Wash	Aged Quinq. Wash
0.1	7.23	13.10	11.24	8.4	12.47	18.33	16.48	13.64
0.2	11.77	12.77	11.06	8.48	17.01	18.01	16.29	13.72
0.3	13.9	11.97	10.3	7.89	19.14	17.20	15.53	13.12
0.4	14.16	10.53	8.88	6.58	19.4	15.77	14.12	11.82

The results are detailed in Sections 4.2.1–4.2.8, which describe the results obtained for each scenario. The tables that are referenced in these sections can be found in Appendix A to the paper.

4.2.1. Aged Cool Roof without Maintenance Full Costs

The NS and PB results for the aged roof without any maintenance are presented in Tables A1 and A2. For both reference roofs, only when heat pumps were used for heating, some savings were found. Likewise, it was observed that the smaller was the absorptivity of the cool roof, the greater was the savings.

For the reference roof with $abs_{ref} = 0.8$, savings only occurred for a differential $i - d$ greater than or equal to 2.7% when the cool roofs' absorptivities were 0.1, 0.2, and 0.3, while for $abs_{cool} = 0.4$, savings were found only if the differential $i - d$ was greater than 3%. The best result in this case was a savings of 5.09 €/m^2 with a payback of 16.43 years that was obtained for the roof with $abs_{cool} = 0.1$ and for the economic indicators $d = 0.3\%$, $i = 6\%$.

For the reference roof with $abs_{ref} = 0.9$, savings were higher than for the case of $abs_{ref} = 0.8$. Now, for the cool roof with $abs_{cool} = 0.1$, savings happened for all the economic scenarios except when $d = 3\%$ and $i = 0\%$, that is for a negative differential $i - d$ equal to -3%. For cool roofs with $abs_{cool} = 0.2$ and 0.3, savings required values of the differential $i - d$ equal to or greater than -1.5%. Finally, for $abs_{cool} = 0.4$, savings required a strictly positive differential $i - d$. The best result in this case was a savings of 10.32 €/m^2 with a payback of 12.33 years, which was obtained for the cool roof $abs_{cool} = 0.1$ and the economic indicators $d = 0.3\%$, $i = 6\%$.

4.2.2. Aged Cool Roof without Maintenance Marginal Costs

The results of the case of the aged roof without maintenance considering marginal costs are presented in Tables A3 and A4. In this case, the savings were called marginal savings. They showed once again a tendency to take higher savings as the absorptivity of the cool roof decreased, the savings attained for the reference roof $abs_{ref} = 0.9$ being higher.

The best results were a savings of 13.10 €/m^2 with a payback of 3.73 years and a savings of 18.33 €/m^2 with a payback of 2.83 years for the reference roofs $abs_{ref} = 0.8$ and $abs_{ref} = 0.9$, respectively, which were both obtained for the cool roof with $abs_{cool} = 0.1$ and $d = 0.3\%$, $i = 6\%$.

It is worth noting that for economic scenarios with a lower inflation differential, good results were also achieved. Therefore, for the case of $d = 0.3\%$, $i = 0\%$, which gave a negative differential, savings of 6.4, 6.27, 5.86, and 5.10 €/m^2 and payback periods of 4.05, 3.91, 3.97, and 4.32 years were obtained for cool roofs with absorptivities 0.1, 0.2, 0.3, and 0.4, respectively, when the reference roof had $abs_{ref} = 0.8$. For the same economic scenario for $abs_{ref} = 0.9$, the marginal savings were greater, being 9.26, 9.13, 8.72, and 7.96 €/m^2, and the payback periods were 2.99, 2.86, 2.85, and 3.01 years for the same cool roof absorptivities.

In this case, a small amount of savings was also obtained when gas was used for heating, but only for $abs_{cool} = 0.4$.

4.2.3. Aged Cool Roof with Decennial Maintenance Full Costs

The results for the aged cool roof with decennial maintenance full costs are shown in Tables A5 and A6. It can be observed that including the maintenance costs penalized the LCA savings of refurbishing with cool paint when compared with the previous case of no maintenance.

Again, only heating with a pump gave savings. The biggest savings were 3.23 €/m^2 with a payback of 14.07 years and a savings of 8.47 €/m^2 with a payback of 2.83 years for the reference roofs $abs_{ref} = 0.8$ and $abs_{ref} = 0.9$, respectively. Both results were obtained for $abs_{cool} = 0.1$ and $d = 0.3\%$, $i = 6\%$.

As in the previous cases, the decrease in absorptivity was associated with an increase in savings and higher savings for $abs_{ref} = 0.9$ than for $abs_{ref} = 0.8$.

Now, the inflation differential required to get savings for $abs_{ref} = 0.8$ was greater than 4.5% for $abs_{cool} = 0.1\%$, 0.2%, and 0.3% and equal to 5.7% for $abs_{cool} = 0.4$. For $abs_{ref} = 0.9$, savings were obtained if the differential was greater than or equal to 1.5% for $abs_{cool} = 0.1\%$, 0.2%, and 0.3% and greater than 2.7% for $abs_{cool} = 0.4$.

4.2.4. Aged Cool Roof with Decennial Maintenance Marginal Costs

The results for the aged cool roof with decennial maintenance and marginal costs are shown in Tables A7 and A8.

Once again, savings were found only if the heating worked through the heat pump, which led to savings for all the economic scenarios considered. Likewise, smaller values of absorptivity produced greater savings, which took the larger values for the reference roof with $abs_{ref} = 0.9$.

The best result for the reference roof $abs_{ref} = 0.9$ was a savings of 16.48 €/m^2 with a payback of 2.13 obtained for $d = 0.3\%$, $i = 6\%$ and for the reference roof $abs_{ref} = 0.8$, a saving of 11.24 €/m^2 with a payback of 3.73 and the same economic indicators.

Now, the inflation differential required to get savings for $abs_{ref} = 0.8$ was greater than 4.5% for $abs_{cool} = 0.1\%$, 0.2%, and 0.3% and equal to 5.7% for $abs_{cool} = 0.4$. For $abs_{ref} = 0.9$, savings were obtained if the differential was greater than or equal to 1.5% for $abs_{cool} = 0.1\%$, 0.2%, and 0.3% and greater than 2.7% for $abs_{cool} = 0.4$.

4.2.5. Aged Cool Roof with Quinquennial Maintenance Full Costs

The results for the aged cool roof with quinquennial maintenance and full costs are shown in Tables A9 and A10. The most relevant fact of this case was that for almost all the studied scenarios, there were no savings. Specifically, for the reference roof with $abs_{ref} = 0.8$, there were no savings in any case, while for the reference roof with $abs_{ref} = 0.9$, only for the differential $i - d$ equal to or greater than 4.5%, some savings were found. The best results in this case were obtained for $abs_{cool} = 0.2$, the greater savings equal to 4.51 €/m^2 with a payback of 17.01 obtained for $d = 0.3\%$, $i = 6\%$.

4.2.6. Aged Cool Roof with Quinquennial Maintenance Marginal Costs

The results for the aged cool roof with quinquennial maintenance and marginal costs are shown in Tables A11 and A12.

As in the previous cases, savings were found only for heating using heat pumps and existed for all absorptivity and economic scenarios considered. The greatest savings were given for $abs_{cool} = 0.2$ for both reference roof absorptivities, the savings for $abs_{ref} = 0.9$ being greater than the ones for $abs_{ref} = 0.8$ for equivalent economic indicators.

For $abs_{ref} = 0.8$, the greatest value was a savings of 8.48 €/m^2 with a payback of 3.73 years, and for $abs_{ref} = 0.9$, the greatest savings was 13.72 €/m^2 with a payback of 2.71 both for $d = 0.3\%$ and $i = 6\%$.

4.2.7. No Aged Cool Roof Full Costs

In Tables A13–A16, results are presented for the case of the non-aged roof with full costs. Although this case may be considered unrealistic, in the literature, it is a frequently treated case. For this reason and because it can give information on the importance of the aging effect when comparing both cases, its results are included here. Maintenance was not considered in the LCA of this case because the non-aged effect made it unnecessary.

For the case of full costs (Tables A13 and A14), savings were found only when heat pumps were used for heating.

Savings were greater for $abs_{ref} = 0.9$ than for $abs_{ref} = 0.8$ under the same economic scenarios. When existing, savings increased as the absorptivity of the cool roofs grew, giving $abs_{cool} = 0.4$ the highest savings both for $abs_{ref} = 0.8$ and $abs_{ref} = 0.9$.

Specifically, when $abs_{ref} = 0.8$, there were no savings for $abs_{cool} = 0.1$; there were savings for $abs_{cool} = 0.2$ if the economic differential $i - d$ was equal to or greater than 2.7%; and there were savings as well for $abs_{cool} = 0.3$ and $abs_{cool} = 0.4$ if the inflation differential was equal to or greater than 1.5%.

When $abs_{ref} = 0.9$, there were savings for $abs_{cool} = 0.1$ if the inflation differential was equal to or greater than 2.7%, for $abs_{cool} = 0.2$ if the inflation differential was equal to or greater than -0.3%, while for $abs_{cool} = 0.3$ and $abs_{cool} = 0.4$, the only scenario for which there were no savings was when $d = 0.3\%$ and $i = 6\%$, which involved a strong negative economic differential $i - d = -3\%$.

The highest savings for $abs_{ref} = 0.8$ was 6.15 €/m^2 with a payback of 14.45 years obtained when $abs_{cool} = 0.4$, $d = 0.3\%$, and $i = 6\%$. For $abs_{ref} = 0.9$, the greatest savings was 11.39 €/m^2 with a payback of 11.76 years and the same economic parameters.

4.2.8. No Aged Cool Roof Marginal Costs

In Tables A15 and A16, marginal savings are presented. It can be pointed out again that savings were found only if heat pumps were used for heating. In this case, savings existed in all the absorptivity and economic scenarios analyzed.

The savings took an increasing value from $abs_{cool} = 0.1$ to $abs_{cool} = 0.4$. This way, the greatest values of the savings were found for $abs_{cool} = 0.4$ for both reference roofs.

For $abs_{ref} = 0.8$, the greatest savings was 14.16 €/m^2 with a payback of 3.09 years, and for $abs_{ref} = 0.9$, the greatest savings was 17.01 €/m^2 with a payback of 2.64 years both for $d = 0.3\%$ and $i = 6\%$.

5. Discussion

For the climatic zone under consideration and the building case study, the results presented in Section 4.1 indicated a decrease in the annual total load for roofs when the absorptivity of the external coating of the roof decreased. This way, a decrease close to 32% when comparing a reference roof of $abs_{ref} = 0.9$ to a cool roof of $abs_{cool} = 0.1$ was found, as is shown in Figure 7. As can be observed in this figure, the pattern found was the following: the less absorptive of the roof, the lower was the cooling load and the higher the heating load, in such a way that the increase in the heating load was clearly compensated by the decrease in the cooling load as the absorptivity decreased and fell within the range of what was a cool roof, that is for absorptivity values less than or equal to five [7].

Furthermore, it can be established from Figure 11 that the effect of the change in absorptivity values was greater on cooling loads than on heating ones. That is, when absorptivity decreased, the decrease of cooling loads was proportionally much greater than the increase of heating loads. This meant that the effect of changes in absorptivity produced a noticeably greater impact on cooling loads than on heating ones.

The energy analysis showed that for the different cases of cool roofs under consideration, that is aged without washing, aged with decennial and quinquennial washing, and non-aged, for the entire LC time period of twenty years, the total loads had very similar results for each value of the cool roof absorptivity; see Figure 13a,b and Table 4. This meant that maintenance through power washing did not have a significant effect on the energy behavior of the cool roof, a fact that has been mentioned in the literature [40]. For the case of no aging effect, smaller values of the total loads were found; this suggested the need to consider the aging effect to have a realistic energy analysis, as was stated in the previous literature [28,40].

For the life cycle's total period, energy savings were found for the four cool roofs' absorptivities and for the two reference roofs studied for all the aged cases considered; see Table 4. For the reference roof $abs_{ref} = 0.9$, the savings ranged between 1.946 GJ/m^2 obtained for $abs_{cool} = 0.1$ and 1.445 GJ/m^2 obtained for $abs_{cool} = 0.4$. For the reference roof $abs_{ref} = 0.8$, the savings were less than for $abs_{ref} = 0.9$, and they were in a range between 1.519 GJ/m^2 obtained for $abs_{cool} = 0.1$ and 1.018 GJ/m^2 obtained for $abs_{cool} = 0.1$.

As can be noted in Table 4, the differences in the energy savings induced by the washing of the cool roofs were very small for the LCA total period, which cast doubt on its advisability, especially when taking into account possible damage to the cool coating when performing maintenance [40].

For the non-aged case, as observed in Figure 13a,b and Table 4, the total loads were the smallest, and consequently, the savings obtained in this case were the greatest. However, as mentioned before, this case could be considered unrealistic, so its results should be taken into account only as a reference by means of which both scenarios (aged and non-aged roofs) could be contrasted while determining the influence of the aging effect on the energy behavior of cool roofs during the LCA period of time.

Regarding the LCA economic analysis, the first issue to highlight was that, generally, economic savings were only obtained when the heat pump was used for heating. The other heating systems considered did not provide savings, except in the specific case of aged roofs without maintenance, in which for the case of $abs_{cool} = 0.4$, some marginal savings were obtained for gas heating; see Tables A3 and A4. This was due to the fact that, in spite of the considerable decrease in total loads pointed out in the energy analysis, the effects of the cost of energy for heating gave rise to an increase in the heat load, which from an economic point of view, was not compensated with the decrease in the refrigeration load, the only exception to this being the case of an even system of energy efficiency for heating and cooling as provided by heat pumps.

On the other hand, whether rehabilitation was necessary or not also had a considerable impact on the results of the LCA. If the refurbishment is done because it is necessary, the costs of applying the cool coating layer should be compared with those of applying another type of coating which in the case of the present study was the bituminous paint layer, while the additional cost of the cool roof represented only the marginal cost. On the contrary, if the application of the cool roof was done without the need for rehabilitation, the initial costs were complete when the LCA was performed.

When marginal savings were considered, for all the cases except one, significant economic savings existed as long as the heat pump was used for heating. These marginal savings were greater for the case of no maintenance, while the marginal savings from a ten year maintenance were greater than those obtained from the five year maintenance; see Tables A3, A4, A7, A8, A11 and A12.

The savings obtained in the case of complete costs were logically lower. In this case, the biggest savings were also obtained in the case that maintenance was not performed, while again, the savings from a ten year maintenance gave rise to better results than those obtained from the five year savings; see Tables A1, A2, A5, A6, A9 and A10. Now, when maintenance was considered, there was a noticeable decrease in the number of cases that resulted in savings. These were mainly concentrated in values of the roof reference with absorptivity equal to 0.9 and high values of the economic differential $i - d$. Even for the quinquennial maintenance, there were no savings for any case when the reference absorptivity was 0.8.

Note also that in all scenarios considered for the aged roofs, the best savings results were obtained for the reference roof with $abs_{ref} = 0.9$ and for the lowest values of the cool roof absorptivity.

On the other hand, as can be seen in Tables 5, 6, and A1–A10, the punctual improvement that was obtained after washing in terms of energy loads had a small reflecting in the economic savings.

This was mainly due to the fact that maintenance costs were not counterbalanced enough so as to obtain relevant energy costs savings. A similar result was suggested in [40].

It is also important to point out the role of economic indicators. As evidenced by the LCA savings, the higher the values of the economic differential $i - d$, the higher the values for savings. This was closely related to an increase in the economic benefits provided by cool roofs in the face of high energy prices.

Finally, for the non-aged case, the savings obtained were close to those for the aged case with no maintenance; see Tables A5 and A6. However, now, the different heat dynamics throughout the period of time considered implied that the highest savings rates were obtained for cool roofs with the highest values. Specifically, the greatest savings were obtained for $abs_{cool} = 0.4$, while for the aged case, they were obtained for $abs_{cool} = 0.1$. The same can be stated for the non-aged case marginal savings: values close to the marginal savings from the aged case with no maintenance, but with the same behavior related to the absorptivities.

Although the performed analysis seemed to point out the existence of benefits when using cool roofs to refurbish the obsolete energy conditions of the social housing stock under study, some extra analysis must be done in order to assess its social impact and to identify the steps that the involved parties, that is tenants, social services, municipality, etc., should take in order to exploit the advantages of this kind of energy improvement. Some research about the topic of social impacts and stakeholder analysis as that made in [31] could help to clarify the role of social agents regarding the implementation of the proposed refurbishment measures.

Thus, taking into account the social implications of the analysis made in this work, it could be useful in order to shed light on the social implications of the present research to perform a Life Cycle Sustainability Assessment (LCSA) [31], which considers environmental LCA, life cycle costing, and Social Life Cycle Assessment (SLCA) [63,64].

6. Conclusions

The energy and economic performances of residential social building roofs retrofitted to become cool roofs were analyzed under the southern Spain climate. The thermal dynamic of the roofs was simulated through a computational code using a finite difference approach in order to assess the impact of different cool coatings when used to retrofit the roofs of dwellings belonging to a promotion of social housing in Seville (Spain) built in the 1960s.

Four different cases of cool coating with values of solar absorptivity equal to 0.1, 0.2, 0.3, and 0.4 when applied to two reference roofs with solar absorptivity equal to 0.8 and 0.9 were analyzed. In order to get realistic simulation conditions, the aging effect of the cool coatings was taken into account by means of designing a pattern of the incidence of the aging effect over the solar absorptivities throughout the service lifetime of the cool roof.

This gave rise to different scenarios regarding the energy behavior of the cool roofs according to the temporary evolution of the cover resulting from the aging effect and the maintenance type considered for the cool coatings.

The results obtained for the different combinations of cool coatings and aging effect pointed to significant savings in the operational energy. This way, a decrease in the annual total loads for roofs was found. Such decreases were larger as the absorptivity of the external coating of the retrofitted roof was reduced. The maximum decrease found was close to 32%, and it was obtained when a roof with solar absorptivity equal to 0.9 was retrofitted with a cool paint with solar absorptivity equal to 0.1.

Moreover, the limited role played by the cool roofs' maintenance over the total loads during the LCA period of time was revealed, since the values of such loads were similar to each of the cool absorptivities considered. However, some variations in the evolution of the heating and cooling loads were observed.

In order to evaluate the economic value of using cool roofs for social housing rehabilitation, a 20 year life cycle analysis was conducted. To carry out a comprehensive LCA analysis, a variety of values for the variables of solar absorptivity, cool roof maintenance, energy and maintenance costs, monetary discount rate, conditioning equipment, and installation cost were taken into account.

The LCA analysis pointed out that initial costs had a strong impact on the economic results. This way, if the costs of the cool coating were not compared to any other roof retrofit, savings were only obtained when, in the case of heating, the equipment used was a heat pump and the economic differential between the energy inflation costs and the monetary discount rate was high. Namely, the best result was found when an aged cool roof without maintenance was used and the cool absorptivity was equal to 0.1, while the reference absorptivity equaled 0.9, and the economic indicators were $d = 0.3\%$ and $i = 6\%$. Following this, the economic LCA savings was 10.32 €/m^2, and the payback period was 12.33 years.

If marginal costs were considered, the LCA analysis reported savings for all the scenarios studied as long as heating was carried out by means of pump heating. In this case, the best result was found again for the case of an aged cool roof without maintenance when the cool absorptivity was equal to 0.1, the reference absorptivity was equal to 0.9, and the economic indicators were $d = 0.3\%$ and $i = 6\%$. The economic LCA savings was now 18.33 €/m^2, and the payback period was 2.83 years.

Another result confirmed in the LCA analysis was the impact of the economic differential $i - d$ on the savings. High values of such a differential yielded higher economic savings and consequently shorter payback periods. This result, which could be considered as expected, was ratified by means of the implemented cost-effectiveness analysis and the fact that investments in refurbishment seeking to reduce energy consumption were from a purely economic standpoint more profitable within raising energy price scenarios.

Furthermore, its use gave rise to economic savings when adequate equipment to condition dwellings was used. Finally, other results described in the literature such as the scarce economic gains stemming from a power washing of this kind of cool coating were revealed for the time period in which the LCA was carried out.

According to the obtained results, in terms of energy consumption and environmental benefits, the use of cool coatings with a solar absorptivity as low as possible is recommended for the rehabilitation of cool roofs in the social building case study in the climatic zone under consideration.

The main limitation of this study rested on the lack of social information on the valuation of all the involved parties of the society, that is tenants, social services, municipality etc., of the application of the present research results. This could be a venue of future research together with the extension of the analysis implemented with the aim of broadening such analysis along the lines of an LCSA considering environmental LCA, life cycle costing, and SLCA.

Author Contributions: Conceptualization, all the authors; methodology, all the authors; software, all the authors; formal analysis, all the authors; investigation, all the authors; writing, original draft preparation, H.D.-T. and C.-A.D.-T.; writing, review and editing, all the authors. All authors read and agreed to the published version of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. LCA Savings

Table A1. LCA savings for the aged roof without maintenance vs. the reference roof with absorptivity = 0.8.

		Absorptivity Solar: 0.1 vs. 0.8						**Absorptivity Solar: 0.2 vs. 0.8**					
		Gas		**Electr.**		**Pump**		**Gas**		**Electr.**		**Pump**	
		Savings	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**
d=0.3%	*i* = 0%	−15.15	-	−62.48	-	−1.6	-	−12.55	-	−50.33	-	−1.73	-
	i = 3%	−16.82	-	−79.59	-	1.14	19.43	−13.41	-	−63.51	-	0.92	19.45
	i = 6%	−19.24	-	−104.24	-	5.09	16.43	−14.65	-	−82.49	-	4.76	16.43
d=1.5%	*i* = 0%	14.58	-	−56.69	-	−2.52	-	−12.25	-	−45.87	-	−2.63	-
	i = 3%	−15.99	-	−71.1	-	−0.2	-	−12.98	-	−57.01	-	−0.38	-
	i = 6%	−18.02	-	−91.85	-	3.11	16.48	−14.02	-	−72.94	-	2.83	18.47
d=3%	*i* = 0%	−13.98	-	−50.69	-	−3.47	-	−11.94	-	−41.25	-	−3.55	-
	i = 3%	−15.14	-	−62.5	-	−1.58	-	−12.54	-	−50.34	-	−1.72	-
	i = 6%	−16.78	-	−79.24	-	1.1	19.45	−13.38	-	−63.23	-	0.88	19.46
		Absorptivity Solar: 0.3 vs. 0.8						**Absorptivity Solar: 0.4 vs. 0.8**					
		Gas		**Electr.**		**Pump**		**Gas**		**Electr.**		**Pump**	
		Savings	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**
d=0.3%	*i* = 0%	−10.34	-	−38.98	-	−2.14	-	−8.7	-	−28.97	-	−2.9	-
	i = 3%	−10.5	-	−48.46	-	0.35	19.57	−8.35	-	−35.18	-	−0.67	-
	i = 6%	−10.74	-	−62.11	-	3.96	16.5	−7.85	-	−44.13	-	2.52	18.529
d=1.5%	*i* = 0%	−10.28	-	−35.77	-	−2.98	-	−8.82	-	−26.87	-	−3.65	-
	i = 3%	−10.42	-	−43.78	-	−0.87	-	−8.52	-	−32.12	-	−1.77	-
	i = 6%	−10.62	-	−55.25	-	2.15	18.37	−8.1	-	−39.63	-	0.91	19.43
d=3%	*i* = 0%	−10.21	-	−32.44	-	−3.85	-	−8.93	-	−24.68	-	−4.42	-
	i = 3%	−10.33	-	−38.98	-	−2.12	-	−8.69	-	−28.97	-	−2.89	-
	i = 6%	−10.49	-	−48.26	-	0.31	19.58	−8.35	-	−35.05	-	−0.71	-

Table A2. LCA savings for the aged roof without maintenance vs. the reference roof with absorptivity = 0.9.

		Absorptivity Solar: 0.1 vs. 0.9						**Absorptivity Solar: 0.2 vs. 0.9**					
		Gas		**Electr.**		**Pump**		**Gas**		**Electr.**		**Pump**	
		Savings	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**
d=0.3%	*i* = 0%	−14.64	-	−70.21	-	1.25	17.639	−12.04	-	−58.06	-	1.12	17.84
	i = 3%	−16.15	-	−89.95	-	4.97	14.327	−12.73	-	−73.86	-	4.75	14.46
	i = 6%	−18.31	-	−118.38	-	10.32	12.33	−13.73	-	−96.63	-	9.99	12.43
d=1.5%	*i* = 0%	−14.13	-	−63.53	-	0.01	19.97	−11.8	-	−52.71	-	−0.09	-
	i = 3%	−15.40	-	−80.22	-	3.15	15.6	−12.39	-	−66.07	-	2.97	15.76
	i = 6%	−17.22	-	−104.09	-	7.64	13.18	−13.22	-	−85.19	-	7.37	13.29
d=3%	*i* = 0%	−13.59	-	−56.62	-	−1.27	-	−11.55	-	−47.18	-	−1.36	-
	i = 3%	−14.63	-	−70.24	-	1.28	17.65	−12.03	-	−58.08	-	1.14	17.86
	i = 6%	−16.11	-	−89.55	-	4.91	14.45	−12.71	-	−73.55	-	4.70	14.58
		Absorptivity Solar: 0.3 vs. 0.9						**Absorptivity Solar: 0.4 vs. 0.9**					
		Gas		**Electr.**		**Pump**		**Gas**		**Electr.**		**Pump**	
		Savings	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**
d=0.3%	*i* = 0%	−9.83	-	−46.71	-	0.71	18.55	−8.2	-	−36.7	-	−0.04	-
	i = 3%	−9.83	-	−58.81	-	4.19	14.92	−7.68	-	−45.54	-	3.15	15.903
	i = 6%	−9.82	-	−76.25	-	9.19	12.78	−6.93	-	−58.27	-	7.76	13.5
d=1.5%	*i* = 0%	−9.83	-	−42.61	-	−0.44	-	−8.3	-	−33.71	-	−1.11	-
	i = 3%	−9.82	-	−52.85	-	2.48	18.32	−7.3	-	−41.18	-	1.58	17.46
	i = 6%	−9.82	-	−67.49	-	6.68	16.3	−13.36	-	−51.87	-	5.45	14.49
d = 3%	*i* = 0%	−9.83	-	−38.38	-	−1.65	-	−8.55	-	−30.62	-	−2.23	-
	i = 3%	−9.82	-	−46.73	-	0.73	18.55	−8.19	-	−36.71	-	−0.02	-
	i = 6%	−9.82	-	−58.57	-	4.13	15.05	−7.68	-	−45.36	-	3.1	16.02

Table A3. LCA marginal savings for the aged cool roof without maintenance vs. the reference roof with absorptivity = 0.8.

		Absorptivity Solar: 0.1 vs. 0.8						Absorptivity Solar: 0.2 vs. 0.8					
		Gas		Electr.		Pump		Gas		Electr.		Pump	
		Savings	PayB	Savings	PayB	Savings	PayB	Savings	PayB	Savings	PayB	Savings	PayB
d=0.3%	i = 0%	−7.14	-	−54.47	-	6.4	4.05	−4.54	-	−42.32	-	6.27	3.91
	i = 3%	−8.81	-	−71.58	-	9.14	3.88	−5.4	-	−55.501	-	8.93	3.75
	i = 6%	−11.23	-	−96.23	-	13.1	3.73	−6.64	-	−74.48	-	12.77	3.61
d=1.5%	i = 0%	−6.57	-	−48.68	-	5.48	4.17	−4.24	-	−37.86	-	5.37	4.03
	i = 3%	−7.98	-	−63.14	-	7.8	3.991	−4.97	-	−49.00	-	7.62	3.859
	i = 6%	−10.01	-	−83.84	-	11.12	3.832	−6.01	-	−63.15	-	10.84	3.70
d=3%	i = 0%	−5.97	-	−42.68	-	4.53	4.33	−3.93	-	−33.24	-	4.45	4.18
	i = 3%	−7.13	-	−54.492	-	6.42	4.13	−4.53	-	−42.33	-	6.28	3.99
	i = 6%	−8.77	-	−71.23	-	9.11	3.959	−5.377	-	−55.22	-	8.89	3.83
		Absorptivity Solar: 0.3 vs. 0.8						Absorptivity Solar: 0.4 vs. 0.8					
		Gas		Electr.		Pump		Gas		Electr.		Pump	
		Savings	PayB	Savings	PayB	Savings	PayB	Savings	PayB	Savings	PayB	Savings	PayB
d=0.3%	i = 0%	−2.33	-	−30.97	-	5.86	3.97	−0.69	-	20.96	-	5.104	4.32
	i = 3%	−2.49	-	−40.45	-	8.36	3.81	−0.34	-	−27.17	-	7.33	4.12
	i = 6%	−2.73	-	−54.1	-	11.97	3.66	0.15	19.6	−36.12	-	10.53	3.95
d=1.5%	i = 0%	−2.27	-	−27.76	-	5.02	4.09	−0.81	-	−18.86	-	4.35	4.46
	i = 3%	−2.41	-	−36.12	-	7.13	3.919	−0.51	-	−24.11	-	6.23	4.24
	i = 6%	−2.61	-	−47.24	-	10.16	3.76	−0.09	-	−31.62	-	8.92	4.06
d=3%	i = 0%	−2.2	-	−24.43	-	4.15	4.26	−0.92	-	−16.67	-	3.58	4.66
	i = 3%	−2.32	-	−30.9	-	5.88	4.06	−0.68	-	−20.96	-	5.11	4.41
	i = 6%	−2.48	-	−40.25	-	8.32	3.89	−0.34	-	−27.04	-	7.29	4.21

Table A4. LCA marginal savings for the aged cool roof without maintenance vs. the reference roof with absorptivity = 0.9.

		Absorptivity Solar: 0.1 vs. 0.9						Absorptivity Solar: 0.2 vs. 0.9					
		Gas		Electr.		Pump		Gas		Electr.		Pump	
		Savings	PayB	Savings	PayB	Savings	PayB	Savings	PayB	Savings	PayB	Savings	PayB
d=0.3%	i = 0%	−6.63	-	−62.2	-	9.26	2.99	−4.03	-	−50.05	-	9.13	2.86
	i = 3%	−8.14	-	−81.94	-	12.98	2.9	−4.72	-	−65.85	-	12.76	2.78
	i = 6%	−10.3	-	110.37	-	18.33	2.83	−5.72	-	−88.62	-	18.01	2.716
d=1.5%	i = 0%	−6.12	-	−55.52	-	8.02	3.05	−3.79	-	−44.7	-	7.91	2.92
	i = 3%	−7.39	-	−72.21	-	11.16	2.96	−4.38	-	−58.06	-	10.98	2.84
	i = 6%	−9.21	-	−96.08	-	15.6	2.88	−5.21	-	−77.18	-	15.38	2.77
d=3%	i = 0%	−5.58	-	−48.61	-	6.73	3.14	−3.54	-	−39.17	-	6.64	3.01
	i = 3%	−6.62	-	−62.23	-	9.29	3.05	−4.02	-	−50.07	-	9.15	2.92
	i = 6%	−8.09	-	−81.54	-	12.92	2.96	−4.70	-	−65.54	-	12.71	2.84
		Absorptivity Solar: 0.3 vs. 0.9						Absorptivity Solar: 0.4 vs. 0.9					
		Gas		Electr.		Pump		Gas		Electr.		Pump	
		Savings	PayB	Savings	PayB	Savings	PayB	Savings	PayB	Savings	PayB	Savings	PayB
d=0.3%	i = 0%	−1.82	-	−38.70	-	8.72	2.85	−0.19	-	−28.69	-	7.96	3.01
	i = 3%	−1.81	-	50.80	-	12.20	2.78	0.32	17.44	−37.53	-	11.16	2.91
	i = 6%	−1.80	-	−68.24	-	17.20	2.71	1.07	14.63	50.26	-	15.77	2.83
d=1.5%	i = 0%	−1.82	-	−34.60	-	7.56	2.92	−0.36	-	−25.70	-	6.89	3.07
	i = 3%	−1.81	-	−44.84	-	10.49	2.84	0.07	19.27	−33.17	-	9.59	2.98
	i = 6%	−1.81	-	−59.48	-	14.69	2.77	0.70	15.75	−43.86	-	13.46	2.90
d=3%	i = 0%	−1.82	-	−30.37	-	6.35	3.01	−0.54	-	−22.6	-	5.77	3.17
	i = 3%	−1.81	-	−38.72	-	8.75	2.92	−0.182	-	−28.7	-	7.98	3.07
	i = 6%	−1.81	-	−50.56	-	12.14	2.84	0.33	17.48	−37.35	-	11.11	2.98

Table A5. LCA savings of the aged roof with 10 years maintenance vs. the reference roof with absorptivity = 0.8.

		Absorptivity Solar: 0.1 vs. 0.8						**Absorptivity Solar: 0.2 vs. 0.8**					
		Gas		**Electr.**		**Pump**		**Gas**		**Electr.**		**Pump**	
		Savings	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**
d=0.3%	*i* = 0%	−17.28	-	−65.64	-	−3.43	-	−14.53	-	−53.08	-	−3.49	-
	i = 3%	−19.06	-	−83.2	-	−0.7	-	−15.44	-	−66.54	-	−0.81	-
	i = 6%	−21.6	-	−108.4	-	3.23	17.18	−16.73	-	−85.86	-	3.05	17.28
d=1.5%	*i* = 0%	−16.64	-	−59.67	-	−4.33	-	−14.19	-	−48.49	-	−4.37	-
	i = 3%	−18.16	-	74.53	-	−2.02	-	−14.96	-	−59.89	-	−2.1	-
	i = 6%	−20.3	-	−95.72	-	1.28	18.64	−16.06	-	−76.13	-	1.13	18.76
d=3%	*i* = 0%	−15.98	-	−53.47	-	−5.25	-	−13.83	-	−43.72	-	−5.27	-
	i = 3%	−17.22	-	−65.62	-	−3.37	-	−14.47	-	−53.04	-	−3.43	-
	i = 6%	−18.97	-	−82.79	-	−0.69	-	−15.36	-	−66.21	-	−0.8	-
		Absorptivity Solar: 0.3 vs. 0.8						**Absorptivity Solar: 0.4 vs. 0.8**					
		Gas		**Electr.**		**Pump**		**Gas**		**Electr.**		**Pump**	
		Savings	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**
d=0.3%	*i* = 0%	−12.25	-	−41.52	-	−3.87	-	−10.56	-	−31.35	-	−4.61	-
	i = 3%	−12.45	-	−51.23	-	−1.3476	-	−10.24	-	−37.75	-	−2.36	-
	i = 6%	−12.71	-	−65.16	-	2.29	17.85	−9.76	-	−46.91	-	0.87	19.1
d=1.5%	*i* = 0%	−12.15	-	−38.2	-	−4.69	-	−5.35	-	−29.15	-	−5.35	-
	i = 3%	−12.32	-	−46.43	-	−2.56	-	−10.37	-	−34.57	-	−3.45	-
	i = 6%	−12.55	-	−58.14	-	0.48	19.43	−9.97	-	−42.28	-	−0.73	-
d=3%	*i* = 0%	−12.05	-	−34.762	-	−5.54	-	−10.73	-	−26.87	-	−6.11	-
	i = 3%	−12.19	-	−41.48	-	−3.81	-	−10.51	-	−31.3	-	−4.56	-
	i = 6%	−12.38	-	−50.98	-	−1.34	-	−10.19	-	−37.56	-	−2.35	-

Table A6. LCA savings of the aged roof with 10 years maintenance vs. the reference roof with absorptivity = 0.9.

		Absorptivity Solar: 0.1 vs. 0.9						**Absorptivity Solar: 0.2 vs. 0.9**					
		Gas		**Electr.**		**Pump**		**Gas**		**Electr.**		**Pump**	
		Savings	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**
d=0.3%	*i* = 0%	−16.77	-	−73.37	-	−0.57	-	−14.02	-	−60.81	-	−0.63	-
	i = 3%	−18.39	-	−93.56	-	3.12	16.58	−14.76	-	−76.9	-	3.02	16.63
	i = 6%	−20.68	-	−122.54	-	8.47	14.07	−15.81	-	−100	-	8.28	14.09
d=1.5%	*i* = 0%	−16.2	-	−66.52	-	−1.79	-	−13.74	-	−55.33	-	−1.83	-
	i = 3%	−17.57	-	−83.6	-	1.33	18.02	14.37	-	−68.95	-	1.24	18.28
	i = 6%	−19.5	-	−107.96	-	5.81	15.08	−15.26	-	−88.37	-	5.66	15.11
d=3%	*i* = 0%	−15.59	-	−59.4	-	−3.05	-	−13.44	-	−49.66	-	−3.07	-
	i = 3%	−16.72	-	−73.36	-	−0.5	-	−13.96	-	−60.79	-	−0.56	-
	i = 6%	−18.29	-	−93.1	-	3.12	16.63	−14.69	-	−76.52	-	3.01	16.68
		Absorptivity Solar: 0.3 vs. 0.9						**Absorptivity Solar: 0.4 vs. 0.9**					
		Gas		**Electr.**		**Pump**		**Gas**		**Electr.**		**Pump**	
		Savings	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**
d=0.3%	*i* = 0%	−11.74	-	−49.25	-	−1.01	-	−10.06	-	−39.08	-	−1.755	-
	i = 3%	−11.77	-	−61.59	-	2.48	17.11	−9.56	-	−48.1	-	1.46	18.16
	i = 6%	11.79	-	−79.29	-	7.52	14.40	−8.83	-	−61.05	-	6.11	15.15
d=1.5%	*i* = 0%	−11.7	-	−45.05	-	−2.16	-	−10.2	-	−36	-	−2.81	-
	i = 3%	−11.73	-	−55.49	-	0.79	18.86	−9.78	-	−43.641	-	−0.09	-
	i = 6%	−11.76	-	−70.38	-	5.02	15.49	−9.17	-	−54.52	-	3.8	16.34
d=3%	*i* = 0%	−11.66	-	−40.696	-	−3.35	-	−10.34	-	−32.8	-	−3.91	-
	i = 3%	−11.68	-	−49.23	-	−0.941	-	−10	-	−39.05	-	−1.69	-
	i = 6%	−11.71	-	−61.29	-	2.47	17.15	−9.51	-	−47.87	-	1.46	18.20

Table A7. LCA marginal savings of the aged roof with 10 years maintenance vs. the reference roof with absorptivity = 0.8.

		Absorptivity Solar: 0.1 vs. 0.8						Absorptivity Solar: 0.2 vs. 0.8					
		Gas		Electr.		Pump		Gas		Electr.		Pump	
		Savings	PayB	Savings	PayB	Savings	PayB	Savings	PayB	Savings	PayB	Savings	PayB
d=0.3%	*i* = 0%	−9.27	-	−57.63	-	4.571	4.05	−6.52	-	−45.07	-	4.51	3.91
	i = 3%	−11.05	-	−75.19	-	7.3	3.88	−7.43	-	−58.53	-	7.19	3.75
	i = 6%	−13.59	-	−100.39	-	11.24	3.73	−8.72	-	−77.85	-	11.06	3.61
d=1.5%	*i* = 0%	−8.63	-	−51.66	-	3.67	4.17	−6.18	-	−40.48	-	3.63	4.03
	i = 3%	−10.15	-	−66.52	-	5.98	3.99	−6.96	-	−51.88	-	5.9	3.85
	i = 6%	−12.29	-	−87.71	-	9.29	3.83	−8.051	-	−68.12	-	9.145	3.70
d=3%	*i* = 0%	−12.29	-	−45.46	-	2.75	4.33	−5.82	-	−35.71	-	2.73	4.18
	i = 3%	−7.97	-	−57.61	-	4.63	4.13	−6.46	-	−45.03	-	4.57	3.99
	i = 6%	−10.96	-	−74.78	-	7.31	3.96	−7.35	-	−58.2	-	7.2	3.83
		Absorptivity Solar: 0.3 vs. 0.8						**Absorptivity Solar: 0.4 vs. 0.8**					
		Gas		**Electr.**		**Pump**		**Gas**		**Electr.**		**Pump**	
		Savings	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**
d=0.3%	*i* = 0%	−4.24	-	−33.51	-	4.13	3.97	−2.55	-	−23.34	-	3.39	4.32
	i = 3%	−4.44	-	−43.22	-	6.66	3.81	−2.23	-	−29.74	-	5.64	4.12
	i = 6%	−4.7	-	−57.15	-	10.3	3.66	−1.75	-	−38.9	-	8.88	3.95
d=1.5%	*i* = 0%	−4.14	-	−30.19	-	3.31	4.09	−2.64	-	−21.14	-	2.65	4.46
	i = 3%	−4.32	-	−38.42	-	5.44	3.91	−2.36	-	−26.56	-	4.55	4.24
	i = 6%	−4.54	-	−50.13	-	8.49	3.76	−1.96	-	−34.27	-	7.27	4.06
d=3%	*i* = 0%	−4.04	-	−26.75	-	2.46	4.26	−2.72	-	−18.86	-	1.89	4.66
	i = 3%	−4.18	-	−33.47	-	4.19	4.06	−2.5	-	−23.29	-	3.44	4.41
	i = 6%	−4.37	-	−42.97	-	6.66	3.89	−2.18	-	−29.55	-	5.65	4.21

Table A8. LCA marginal savings of the aged roof with 10 years maintenance vs. the reference roof with absorptivity = 0.9.

		Absorptivity Solar: 0.1 vs. 0.9						Absorptivity Solar: 0.2 vs. 0.9					
		Gas		Electr.		Pump		Gas		Electr.		Pump	
		Savings	PayB	Savings	PayB	Savings	PayB	Savings	PayB	Savings	PayB	Savings	PayB
d=0.3%	*i* = 0%	−8.76	-	−65.36	-	7.434	2.99	−6.01	-	−52.8	-	7.37	2.86
	i = 3%	−10.38	-	−85.55	-	11.13	2.9	−6.75	-	−68.89	-	11.03	2.78
	i = 6%	−12.67	-	−114.53	-	16.48	2.13	−7.8	-	−91.99	-	16.29	2.71
d=1.5%	*i* = 0%	−8.19	-	−58.51	-	6.21	3.05	−5.73	-	−47.32	-	6.17	2.92
	i = 3%	−9.56	-	−75.59	-	9.34	2.96	−6.36	-	−60.94	-	9.25	2.84
	i = 6%	−11.49	-	−99.952	-	13.82	2.88	−7.25	-	−80.36	-	13.67	2.77
d=3%	*i* = 0%	−7.58	-	−51.39	-	4.95	3.14	−5.43	-	−41.65	-	4.93	3.01
	i = 3%	−8.71	-	−65.35	-	7.5	3.05	−5.95	-	−52.78	-	7.44	2.92
	i = 6%	−10.28	-	−85.09	-	11.13	2.96	−6.68	-	−68.51	-	11.02	2.84
		Absorptivity Solar: 0.3 vs. 0.9						**Absorptivity Solar: 0.4 vs. 0.9**					
		Gas		**Electr.**		**Pump**		**Gas**		**Electr.**		**Pump**	
		Savings	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**
d=0.3%	*i* = 0%	−3.73	-	−41.24	-	7.01	2.85	−2.05	-	−31.07	-	6.25	3.02
	i = 3%	−3.76	-	−53.58	-	10.49	2.78	−1.55	-	−40.09	-	9.47	2.91
	i = 6%	−3.78	-	−71.28	-	15.53	2.71	−0.82	-	−53.04	-	14.12	2.83
d=1.5%	*i* = 0%	−3.69	-	−37.04	-	5.84	2.92	−2.19	-	−27.99	-	5.191	3.07
	i = 3%	−3.72	-	−47.48	-	8.8	2.84	−1.77	-	−35.63	-	7.91	2.98
	i = 6%	−3.74	-	−62.37	-	13.03	2.76	−1.16	-	−46.51	-	11.81	2.9
d=3%	*i* = 0%	−3.65	-	−32.68	-	4.65	3.01	−2.33	-	−24.79	-	4.096	3.17
	i = 3%	−3.67	-	−41.22	-	7.06	2.92	−1.99	-	−31.04	-	6.31	3.07
	i = 6%	−3.70	-	−53.28	-	10.49	2.84	−1.50	-	−39.86	-	9.47	2.98

Table A9. LCA savings of the aged roof with 5 years maintenance vs. the reference roof with absorptivity = 0.8.

		Absorptivity Solar: 0.1 vs. 0.8						**Absorptivity Solar: 0.2 vs. 0.8**					
		Gas		**Electr.**		**Pump**		**Gas**		**Electr.**		**Pump**	
		Savings	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**
d=0.3%	i = 0%	−21.73	-	−72.44	-	−7.22	-	−18.7	-	−59.12	-	−7.13	-
	i = 3%	−26.92	-	−91.22	-	−4.59	-	−19.87	-	−73.53	-	−4.5	-
	i = 6%	−21.6	-	−118.16	-	−0.79	-	−21.52	-	−94.21	-	−0.71	-
d=1.5%	i = 0%	−20.94	-	66.01	-	−8.03	-	−18.24	-	−54.17	-	−7.95	-
	i = 3%	−22.75	-	−81.91	-	−5.82	-	−19.23	-	−66.37	-	−5.73	-
	i = 6%	−25.32	-	−104.57	-	−2.63	-	−20.62	-	−83.76	-	−2.55	-
d=3%	i = 0%	−20.1	-	−59.34	-	−8.87	-	−17.74	-	−49.03	-	−8.78	-
	i = 3%	−21.59	-	−72.33	-	−7.06	-	−18.55	-	−59	-	−6.97	-
	i = 6%	−23.68	-	−90.7	-	−4.49	-	−19.69	-	−73.1	-	−4.41	-
		Absorptivity Solar: 0.3 vs. 0.8						**Absorptivity Solar: 0.4 vs. 0.8**					
		Gas		**Electr.**		**Pump**		**Gas**		**Electr.**		**Pump**	
		Savings	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**
d=0.3%	i = 0%	16.23	-	−47.01	-	−7.42	-	−14.4	-	−36.38	-	−8.11	-
	i = 3%	−16.61	-	−57.47	-	−4.92	-	−14.21	-	−43.35	-	−5.86	-
	i = 6%	−17.14	-	−72.46	-	−1.31	-	−13.91	-	−53.34	-	−2.62	-
d=1.5%	i = 0%	16.04	-	−43.41	-	−8.2	-	−14.4	-	−33.96	-	−8.81	-
	i = 3%	−16.36	-	−52.26	-	−6.08	-	−14.24	-	−39.86	-	−6.91	-
	i = 6%	−17.14	-	−72.46	-	−1.31	-	−13.99	-	−48.26	-	−4.18	-
d=1.5%	i = 0%	−15.82	-	−39.65	-	−8.99	-	−14.39	-	−31.43	-	−9.51	-
	i = 3%	−16.09	-	−46.89	-	−7.27	-	−14.26	-	−36.25	-	−7.96	-
	i = 6%	−16.46	-	−57.11	-	−4.82	-	−14.06	-	−43.07	-	−5.76	-

Table A10. LCA savings of the aged roof with 5 years maintenance vs. the reference roof with absorptivity = 0.9.

		Absorptivity Solar: 0.1 vs. 0.9						**Absorptivity Solar: 0.2 vs. 0.9**					
		Gas		**Electr.**		**Pump**		**Gas**		**Electr.**		**Pump**	
		Savings	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**
d=0.3%	i = 0%	−21.23	-	−80.17	-	−4.35	-	−18.19	-	−66.85	-	−4.27	-
	i = 3%	−23.19	-	−101.57	-	−0.75	-	19.87	-	−73.53	-	−4.5	-
	i = 6%	−25.99	-	−132.3	-	4.43	17.11	−20.6	-	−108.35	-	4.51	17.01
d=1.5%	i = 0%	−20.49	-	−72.86	-	−5.5	-	−17.79	-	−61.02	-	−5.41	-
	i = 3%	−22.16	-	−90.97	-	−2.46	-	−18.63	-	−75.44	-	−2.37	-
	i = 6%	−24.52	-	−116.81	-	1.89	18.5	−19.82	-	−96	-	1.97	18.4
d=3%	i = 0%	19.71	-	−65.27	-	−6.67	-	−17.35	-	−54.96	-	−6.59	-
	i = 3%	−21.08	-	−80.08	-	−4.19	-	−18.05	-	−66.75	-	−4.11	-
	i = 6%	−23.01	-	−101.01	-	−0.67	-	−19.02	-	−83.41	-	−0.59	-
		Absorptivity Solar: 0.3 vs. 0.9						**Absorptivity Solar: 0.4 vs. 0.9**					
		Gas		**Electr.**		**Pump**		**Gas**		**Electr.**		**Pump**	
		Savings	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**
d=0.3%	i = 0%	−15.73	-	−54.74	-	−4.56	-	−13.9	-	−44.11	-	−5.25	-
	i = 3%	−15.94	-	−67.82	-	−1.08	-	−13.53	-	−53.71	-	−2.03	-
	i = 6%	−16.22	-	−86.6	-	3.92	17.29	−12.98	-	−67.48	-	2.61	18.08
d=1.5%	i = 0%	−15.59	-	−50.25	-	−5.66	-	−13.96	-	−40.8	-	−6.27	-
	i = 3%	−15.77	-	−61.32	-	−2.73	-	−13.65	-	−48.92	-	−3.55	-
	i = 6%	−16.01	-	−77.1	-	1 1.47	18.76	−13.19	-	−60.5	-	0.34	19.68
d=3%	i = 0%	−15.43	-	−45.59	-	−6.8	-	−14.39	-	−31.43	-	−9.51	-
	i = 3%	−15.58	-	−54.64	-	−4.4	-	−14.26	-	−36.25	-	−7.96	-
	i = 6%	−15.78	-	−67.43	-	−1.01	-	−13.39	-	−53.38	-	−1.94	-

Table A11. LCA marginal savings of the aged roof with 5 years maintenance vs. the reference roof with absorptivity = 0.8.

		Absorptivity Solar: 0.1 vs. 0.8						**Absorptivity Solar: 0.2 vs. 0.8**					
		Gas		**Electr.**		**Pump**		**Gas**		**Electr.**		**Pump**	
		Savings	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**
	i = 0%	−12.53	-	−63.23	-	1.984	4.056	−9.49	-	−49.91	-	2.071	3.91
d=0,3%	*i* = 3%	−14.6675	-	81.52	-	4.61	3.88	−10.66	-	−64.33	-	4.69	3.75
	i = 6%	−17.71	-	−108.95	-	8.4	3.73	−12.32	-	−85.01	-	8.48	3.61
	i = 0%	−11.74	-	−56.82	-	1.15	4.17	−9.047	-	−44.98	-	1.23	4.03
d=1.5%	*i* = 3%	−13.56	-	−72.72	-	3.37	3.99	−10.03	-	−57.18	-	3.45	3.85
	i = 6%	−16.13	-	−95.37	-	6.55	3.83	−11.43	-	−74.57	-	6.63	3.7
	i = 0%	−10.92	-	−50.166	-	0.304	4.33	−8.56	-	−39.85	-	0.38	4.18
d=3%	*i* = 3%	−12.41	-	−63.16	-	2.11	4.131	−9.38	-	−49.83	-	2.19	3.99
	i = 6%	14.5	-	−81.52	-	4.68	3.95	−10.52	-	−63.93	-	4.76	3.833
		Absorptivity Solar: 0.3 vs. 0.8						**Absorptivity Solar: 0.4 vs. 0.8**					
		Gas		**Electr.**		**Pump**		**Gas**		**Electr.**		**Pump**	
		Savings	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**
	i = 0%	−7.03	-	37.812	-	1.78	3.97	−5.2	-	−27.18	-	1.08	4.32
d=0.3%	*i* = 3%	−7.41	-	−48.26	-	4.28	3.811	−5	-	−34.15	-	3.33	4.12
	i = 6%	−7.94	-	−63.25	-	7.89	3.665	−4.7	-	−44.137	-	6.58	3.95
	i = 0%	−6.84	-	−34.21	-	0.98	4.09	−5.21	-	24.76	-	0.37	4.46
d=1.5%	*i* = 3%	−7.17	-	−43.06	-	3.1	3.91	−5.05	-	−30.66	-	2.282	4.24
	i = 6%	−7.62	-	−55.67	-	6.13	3.76	−4.8	-	−39.07	-	5.005	4.06
	i = 0%	−6.64	-	−30.48	-	0.17	4.26	−5.22	-	−22.255	-	−0.34	-
d=3%	*i* = 3%	−6.91	-	−37.72	-	1.9	4.06	−5.08	-	−27.08	-	1.2	4.41
	i = 6%	−7.28	-	−47.94	-	4.35	3.89	−4.89	-	−33.89	-	3.409	4.21

Table A12. LCA marginal savings of the aged roof with 5 years maintenance vs. the reference roof with absorptivity = 0.9.

		Absorptivity Solar: 0.1 vs. 0.9						**Absorptivity Solar: 0.2 vs. 0.9**					
		Gas		**Electr.**		**Pump**		**Gas**		**Electr.**		**Pump**	
		Savings	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**
	i = 0%	−12.02	-	−70.96	-	4.84	2.99	−8.99	-	−57.64	-	4.93	2.86
d=0.3%	*i* = 3%	−13.99	-	−92.36	-	8.44	2.9	−9.98	-	−74.68	-	8.53	2.78
	i = 6%	−16.78	-	−123.097	-	13.64	2.83	−11.39	-	−99.14	-	13.72	2.71
	i = 0%	−11.3	-	−63.66	-	3.68	3.05	−8.6	-	−51.82	-	3.77	2.92
d=1.5%	*i* = 3%	−12.97	-	−81.78	-	6.72	2.96	−9.44	-	−66.25	-	6.81	2.84
	i = 6%	−15.33	-	−107.61	-	11.08	2.88	−10.63	-	−86.81	-	11.17	2.77
	i = 0%	10.54	-	−56.09	-	2.5	3.14	8.18	-	−45.78	-	2.58	3.013
d=3%	*i* = 3%	−11.9	-	−70.9	-	4.97	3.05	−8.87	-	−57.57	-	5.06	2.92
	i = 6%	13.83	-	−91.84	-	8.5	2.96	−9.84	-	−74.24	-	8.58	2.84
		Absorptivity Solar: 0.3 vs. 0.9						**Absorptivity Solar: 0.4 vs. 0.9**					
		Gas		**Electr.**		**Pump**		**Gas**		**Electr.**		**Pump**	
		Savings	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**
	i = 0%	−6.52	-	−45.54	-	4.64	2.85	−4.69	-	−34.912	-	3.95	3.001
d=0.3%	*i* = 3%	−6.73	-	−58.62	-	8.11	2.78	−4.32	-	−44.506	-	7.17	2.91
	i = 6%	−7.02	-	−77.39	-	13.12	2.71	−3.77	-	−58.27	-	11.82	2.83
	i = 0%	−6.4	-	−41.06	-	3.52	2.92	−4.76	-	−31.61	-	2.91	3.07
d=1.5%	*i* = 3%	−6.58	-	−52.13	-	6.46	2.84	−4.46	-	−39.73	-	5.63	2.98
	i = 6%	−6.82	-	−67.91	-	10.66	2.76	−4.01	-	−51.31	-	9.539	2.9
	i = 0%	−6.25	-	−36.41	-	2.37	3.01	−4.83	-	−28.18	-	1.85	3.17
d=3%	*i* = 3%	−6.41	-	−45.46	-	4.76	2.92	−4.58	-	−34.82	-	4.075	3.075
	i = 6%	−6.61	-	−58.25	-	8.17	2.84	4.21	-	−44.2	-	7.22	2.98

Table A13. LCA savings for non-aged cool roofs vs. the reference absorptivity = 0.8.

		Absorptivity Solar: 0.1 vs. 0.8						**Absorptivity Solar: 0.2 vs. 0.8**					
		Gas		**Electr.**		**Pump**		**Gas**		**Electr.**		**Pump**	
		Savings	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**
d=0.3%	*i* = 0%	−29.65	-	−116.8	-	−4.7	-	−22.21	-	−92.06	-	−2.22	-
	i = 3%	−36.51	-	−153.25	-	−3.09	-	−26.55	-	−120.11	-	0.22	19.62
	i = 6%	−46.39	-	−205.78	-	−0.77	-	−32.8	-	−160.533	-	3.76	16.17
d=1.5%	*i* = 0%	−27.34	-	−104.53	-	−5.24	-	−20.75	-	−82.62	-	−3.05	-
	i = 3%	−33.14	-	−135.34	-	−3.88	-	−24.42	-	−106.33	-	−0.97	-
	i = 6%	−41.44	-	−179.44	-	−1.93	-	−29.66	-	−140.26	-	1.99	17.54
d=3%	*i* = 0%	−24.95	-	−91.84	-	−5.8	-	−19.25	-	−72.85	-	−3.9	-
	i = 3%	−29.68	-	−116.99	-	−4.69	-	−22.24	-	−92.2	-	−2.21	-
	i = 6%	−36.4	-	−152.65	-	−3.12	-	−26.48	-	−119.65	-	0.18	19.69
		Absorptivity Solar: 0.3 vs. 0.8						**Absorptivity Solar: 0.4 vs. 0.8**					
		Gas		**Electr.**		**Pump**		**Gas**		**Electr.**		**Pump**	
		Savings	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**
d=0.3%	*i* = 0%	−16.577	-	−70.78	-	−1.05	-	−12.42	-	−52.63	-	−0.91	-
	i = 3%	−18.99	-	−91.61	-	1.79	17.44	−13.43	-	−67.29	-	1.97	17.2
	i = 6%	−22.48	-	−121.63	-	5.89	14.61	−14.89	-	−88.42	-	6.15	14.45
d=1.5%	*i* = 0%	−15.763	-	−63.77	-	−2.01	-	−12.08	-	−47.69	-	−1.89	-
	i = 3%	−17.8091	-	−81.38	-	0.39	19.3	−12.94	-	−60.09	-	0.55	19.02
	i = 6%	−20.73	-	−106.57	-	3.837	15.76	−14.16	-	−77.82	-	4.06	15.57
d=3%	*i* = 0%	−14.92	-	−56.52	-	−3	-	−11.73	-	−42.59	-	−2.9	-
	i = 3%	−16.59	-	−70.89	-	−1.04	-	−12.43	-	−52.7	-	−0.9	-
	i = 6%	−18.95	-	−91.27	-	1.74	17.54	−13.42	-	−67.05	-	1.93	17.31

Table A14. LCA savings for non-aged cool roofs vs. the reference absorptivity = 0.9.

		Absorptivity Solar: 0.1 vs. 0.9						**Absorptivity Solar: 0.2 vs. 0.9**					
		Gas		**Electr.**		**Pump**		**Gas**		**Electr.**		**Pump**	
		Savings	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**
d=0.3%	*i* = 0%	−29.14	-	−124.53	-	−1.84	-	−21.71	-	−99.79	-	0.63	18.69
	i = 3%	−35.83	-	−163.61	-	0.74	18.85	−25.87	-	−130.47	-	4.06	15.01
	i = 6%	−45.47	-	−219.92	-	4.46	15.62	−31.87	-	−174.67	-	9	12.85
d=1.5 %	*i* = 0%	26.89	-	−111.38	-	−2.71	-	−20.31	-	−89.46	-	−0.51	- -
	i = 3%	−32.55	-	−144.41	-	−0.52	-	−23.83	-	−115.73	-	2.38	16.41
	i = 6%	−40.64	-	−191.69	-	2.59	15.62	−28.86	-	−152.83	-	6.52	13.76
d=3%	*i* = 0%	−24.56	-	−97.78	-	−3.61	-	−18.86	-	−78.78	-	−1.7	-
	i = 3%	−29.18	-	−124.73	-	−1.82	-	−21.73	-	−99.94	-	0.65	18.7
	i = 6%	−35.72	-	−162.96	-	0.7	18.93	−25.8	-	−129.96	-	4.01	15.14
		Absorptivity Solar: 0.3 vs. 0.9						**Absorptivity Solar: 0.4 vs. 0.9**					
		Gas		**Electr.**		**Pump**		**Gas**		**Electr.**		**Pump**	
		Savings	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**
d=0.3%	*i* = 0%	−16.0722	-	−78.5192	-	1.8	16.71	−11.92	-	−60.362	-	1.94	16.5
	i = 3%	−18.32	-	−101.97	-	5.62	13.71	−12.76	-	−77.65	-	5.81	13.56
	i = 6%	−21.56	-	−135.76	-	11.13	11.87	−13.97	-	−102.56	-	11.39	11.76
d=1.5 %	*i* = 0%	−15.31	-	−70.6	-	0.52	18.8	−11.63	-	−54.54	-	0.64	18.53
	i = 3%	−17.21	-	−90.45	-	3.74	14.88	−12.34	-	−69.15	-	3.91	14.72
	i = 6%	−19.93	-	−118.81	-	8.37	12.66	−13.363	-	−90.06	-	8.59	12.54
d=3%	*i* = 0%	−14.53	-	−62.46	-	−0.81	-	−11.34	-	−48.5	-	−0.7	-
	i = 3%	−16.39	-	−81.92	-	2.35	16.76	−11.92	-	−60.45	-	1.96	16.55
	i = 6%	−18.28	-	−101.58	-	5.56	13.84	−12.74	-	−77.36	-	5.75	13.7

Table A15. LCA marginal savings for non-aged cool roofs vs. the reference absorptivity = 0.8.

		Absorptivity Solar: 0.1 vs. 0.8						**Absorptivity Solar: 0.2 vs. 0.8**					
		Gas		**Electr.**		**Pump**		**Gas**		**Electr.**		**Pump**	
		Savings	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**
d=0.3%	*i* = 0%	−21.64	-	−108.79	-	3.3	5.94	14.2	-	−84.05	-	5.784	3.89
	i = 3%	−28.5	-	−145.24	-	4.916	5.54	−18.54	-	−112.10	-	8.23	3.73
	i = 6%	−38.38	-	−197.77	-	7.23	5.22	−24.79	-	−152.52	-	11.77	3.59
d=1.5%	*i* = 0%	−19.33	-	−96.52	-	2.76	6.2	−12.74	-	−74.61	-	4.959	4.01
	i = 3%	−25.13	-	−127.33	-	4.12	5.76	−16.414	-	−98.32	-	7.03	3.839
	i = 6%	−33.431	-	−171.4	-	6.07	5.4	−21.65	-	−132.25	-	10	3.69
d=3%	*i* = 0%	−16.94	-	−83.83	-	2.2	6.57	−11.24	-	−64.84	-	4.10	4.16
	i = 3%	−21.60	-	−108.98	-	3.31	6.05	−14.23	-	−84.19	-	5.79	3.97
	i = 6%	−28.30	-	−144.64	-	4.88	5.65	−18.47	-	−111.64	-	8.19	3.81
		Absorptivity Solar: 0.3 vs. 0.8						**Absorptivity Solar: 0.4 vs. 0.8**					
		Gas		**Electr.**		**Pump**		**Gas**		**Electr.**		**Pump**	
		Savings	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**
d=0.3%	*i* = 0%	−8.56	-	−62.7788	-	6.95	3.34	−4.41	-	−44.62	-	7.09	3.29
	i = 3%	−10.98	-	−83.6	-	9.80	3.23	−5.42	-	−59.28	-	9.98	3.18
	i = 6%	−14.47	-	−113.62	-	13.9	3.13	−6.88	-	−80.41	-	14.16	3.09
d=1.5%	*i* = 0%	−7.75	-	−55.769	-	5.99	3.43	−4.07	-	−39.687	-	6.1171	3.38
	i = 3%	−9.79	-	−73.37	-	8.4	3.31	−4.93	-	−52.08	-	8.56	3.26
	i = 6%	−12.72	-	−98.56	-	11.84	3.21	−6.15	-	−69.81	-	12.07	3.16
d=3%	*i* = 0%	−6.52	-	−54.45	-	7.19	2.61	−3.72	-	−34.58	-	5.1	3.49
	i = 3%	−8.07	-	−70.62	-	9.8	2.55	−4.42	-	−44.69	-	7.1	3.36
	i = 6%	−10.27	-	−93.57	-	13.57	2.49	−5.41	-	−59.04	-	9.94	3.25

Table A16. LCA marginal savings for non-aged cool roofs vs. the reference absorptivity = 0.9.

		Absorptivity Solar: 0.1 vs. 0.9						**Absorptivity Solar: 0.2 vs. 0.9**					
		Gas		**Electr.**		**Pump**		**Gas**		**Electr.**		**Pump**	
		Savings	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**
d=0.3%	*i* = 0%	−21.13	-	−116.52	-	6.16	3.69	−13.7	-	−91.78	-	8.64	2.78
	i = 3%	−27.82	-	−155.60	-	8.7	3.55	−17.86	-	122.46	-	12.07	2.7
	i = 6%	−37.46	-	−211.91	-	12.47	3.42	−23.86	-	−166.66	-	17.01	2.64
d=1.5%	*i* = 0%	−18.88	-	−103.37	-	5.29	3.8	−12.3	-	−81.45	-	7.49	2.84
	i = 3%	−24.54	-	−136.4	-	7.482	3.64	−15.82	-	−107.38	-	10.39	2.77
	i = 6%	−32.63	-	−183.67	-	10.6	3.51	−20.85	-	−144.49	-	14.53	2.7
d=3%	*i* = 0%	−16.55	-	−89.77	-	4.39	3.94	−10.85	-	−70.77	-	6.302	2.93
	i = 3%	−21.17	-	−116.72	-	6.18	3.77	−13.7	-	−91.93	-	8.66	2.84
	i = 6%	−27.71	-	−154.95	-	8.709	3.63	−17.79	-	−121.95	-	12.01	2.77
		Absorptivity Solar: 0.3 vs. 0.9						**Absorptivity Solar: 0.4 vs. 0.9**					
		Gas		**Electr.**		**Pump**		**Gas**		**Electr.**		**Pump**	
		Savings	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**	**Savings**	**PayB**
d=0.3%	*i* = 0%	−8.06	-	−70.5	-	9.81	2.49	−3.91	-	−52.35	-	9.95	2.46
	i = 3%	−10.31	-	−93.96	-	13.63	2.43	−4.75	-	−69.64	-	13.82	2.41
	i = 6%	−13.55	-	−127.75	-	19.14	2.38	−5.96	-	−94.55	-	19.4	2.35
d=1.5%	*i* = 0%	−7.3	-	−62.61	-	8.52	2.54	−3.62	-	−46.53	-	8.65	2.51
	i = 3%	−9.2	-	−82.44	-	11.75	2.48	−4.33	-	−61.14	-	11.92	2.45
	i = 6%	−11.92	-	−110.8	-	16.38	2.43	−5.35	-	−82.05	-	16.6	2.4
d=3%	*i* = 0%	−6.52	-	−54.45	-	7.19	2.61	−3.33	-	−40.51	-	7.3	2.58
	i = 3%	−8.07	-	−70.62	-	9.8	2.55	−3.91	-	−52.44	-	9.97	2.52
	i = 6%	−10.27	-	−93.57	-	13.57	2.49	−4.73	-	−69.35	-	13.76	2.46

References

1. Financing the Energy Renovation of Buildings with Cohesion Policy Funding. ISBN 978-92-79-35999-6. Available online: https://op.europa.eu/en/publication-detail/publication/4ef2fc24-67d0-45c2-a6d1-c677574e6d26/language-en (accessed on 14 January 2020).
2. European Commission. DG Energy. Available online: https://ec.europa.eu/clima/policies/strategies/2030-en (accessed on 14 January 2020).
3. Spanish Royal Decrete 2429/1979. *Approving the Basic Building on Thermal Conditions in Buildings NBE-CT-79*; Gobierno de Espaã: Madrid, Spain, 1979; pp. 24524–24550.

4. Synnefa, A. *Cool Roofs Standars and the ECRC Product Rating Program*; European Cool Roofs Council: Brussels, Belgium, 2016.
5. Hernández-Pérez, I.; Alvarez, G.; Xamán, J.; Zavala-Guillén, I.; Arce, J.; Simá, E. Thermal performance of reflective materials applied to exterior building components—A review. *Energy Build.* **2014**, *80*, 81–105. [CrossRef]
6. Lu, X.; Xu, P.; Wang, H.; Yang, T.; Hou, J. Cooling potential and applications prospects of passive radiative cooling in buildings: The current state-of-the-art. *Renew. Sustain. Energy Rev.* **2016**, *65*, 1079–1097. [CrossRef]
7. ES-ENERGY STAR. Roof Products Specification. 2007. Available online: https://www.energystar.gov/products/building-products/roof-products (accessed on 24 January 2020).
8. APEC Energy Working Group. Cool Roofs in APEC Economies: Review of Experience, Best Practices and Potential Benefits. 2011. Available online: https://www.coolrooftoolkit.org/wp-content/uploads/2012/05/APEC-Cool-Roofs.pdf (accessed on 24 January 2020).
9. Akbari, H.; Levinson, R.; Rainer, L. Monitoring the energy-use effects of cool roofs on California commercial buildings. *Energy Build.* **2005**, *37*, 1007–1016. [CrossRef]
10. Romeo, C.; Zinzi, M. Impact of a cool roof application on the energy and comfort performance in an existing non-residential building. A Sicilian case study. *Energy Build.* **2013**, *67*, 647–657. [CrossRef]
11. Akbari, H.; Bretz, S.; Kurn, D.M.; Hanford, J. Peak power and cooling energy savings of high-albedo roofs. *Energy Build.* **1997**, *25*, 117–126. [CrossRef]
12. Akbari, H.; Levinson, R. Evolution of cool-Roof standards in the US. *Adv. Build. Energy Res.* **2008**, *2*, 1–32. [CrossRef]
13. Akbari, H.; Konopacki, S. Calculating energy-saving potentials of heat-island reduction strategies. *Energy Policy* **2005**, *33*, 721–756. [CrossRef]
14. Akbari, H.; Matthews, H.D. Global cooling updates: Reflective roofs and pavements. *Energy Build.* **2012**, *55*, 2–6. [CrossRef]
15. Xu, T.; Sathaye, J.; Akbari, H.; Garg, V.; Tetali, S. Quantifying the direct benefits of cool roofs in an urban setting: Reduced cooling energy use and lowered greenhouse gas emissions. *Build. Environ.* **2012**, *48*, 1–6. [CrossRef]
16. Bozonnet, E.; Doya, M.; Allard, F. Cool roofs impact on building thermal response: A French case study. *Energy Build.* **2011**, *43*, 3006–3012. [CrossRef]
17. Santamouris, M. Cooling the cities—A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. *Sol. Energy* **2014**, *103*, 682–703. [CrossRef]
18. Seifhashem, M.; Capra, B.R.; Milller, W.; Bell, J. The potential for cool roofs to improve the energy efficiency of single storey warehouse-type retail buildings in Australia: A simulation case study. *Energy Build.* **2018**, *158*, 1393–1403. [CrossRef]
19. Boixo, S.; Diaz-Vicente, M.; Colmenar, A.; Castro, M.A. Potential energy savings from cool roofs in Spain and Andalusia. *Energy* **2012**, *38*, 425–438. [CrossRef]
20. Pisello, A.L.; Santamouris, M.; Cotana, F. Active cool roof effect: Impact of cool roofs on cooling system efficiency. *Adv. Build. Energy Res.* **2013**, *7*, 209–221. [CrossRef]
21. Kolokotroni, M.; Gowreesunker, B.L.; Giridharan, R. Cool roof technology in London: An experimental and modelling study. *Energy Build.* **2013**, *67*, 658–667. [CrossRef]
22. De Masi, R.F.; Ruggiero, S.; Vanoli, G.P. Acrylic white paint of industrial sector for cool roofing application: Experimental investigation of summer behavior and aging problem under Mediterranean climate. *Sol. Energy* **2018**, *169*, 468–487. [CrossRef]
23. Levinson, R.; Akbari, H. Potential benefits of cool roofs on commercial buildings: Conserving energy, saving money, and reducing emission ofgreenhouse gases and air pollutants. *Energy Effic.* **2010**, *3*, 53–109. [CrossRef]
24. Hernández-Pérez, I.; Xamán, J.; Macías-Melo, E.V.; Aguilar-Castro, K.M. Reflective materials for cost-effective energy-efficient retrofitting of roofs. In *Cost-Effective Energy-Efficient Building Retrofitting*; Woodhead Publishing: Mexico City, Mexico, 2017; Chapter 4, pp. 119–139.
25. Zhang, Z.; Tong, S.; Yu, H. Life Cycle Analysis of Cool Roof in Tropical Areas. *Procedia Eng.* **2016**, *169*, 392–399. [CrossRef]

26. Jo, J.H.; Carlson, J.D.; Golden, J.S.; Bryan, H. An integrated empirical and modeling methodology for analyzing solar reflective roof technologies on commercial buildings. *Build. Environ.* **2010**, *45*, 453–460. [CrossRef]
27. Yuan, J.; Farnham, C.; Emura, K.; Alam, M.A. Proposal for optimum combination of reflectivity and insulation thickness of building exterior walls for annual thermal load in Japan. *Build. Environ.* **2016**, *103*, 228–237. [CrossRef]
28. Saafi, K.; Daouas, N. A life cycle cost analysis for an optimum combination of cool coating and thermal insulation of residential building roofs in Tunisia. *Energy* **2018**, *152*, 925–938. [CrossRef]
29. Favi, C.; Di Giuseppe, E.; D'Orazio, M.; Rossi, M.; Germani, M. Building Retrofit Measures and Design: A Probabilistic Approach for LCA. *Sustainability* **2018**, *10*, 3655. [CrossRef]
30. Trovato, M.R.; Nocera, F.; Giuffrida, S. Life-Cycle Assessment and Monetary Measurements for the Carbon Footprint Reduction of Public Buildings. *Sustainability* **2020**, *12*, 3460. [CrossRef]
31. Falcone, P.M.; González García, S.; Imbert, E.; Lijó, L.; Moreira, M.T.; Tani, A.; Tartiu, V.E.; Morone, P. Transitioning towards the bio-economy: Assessing the social dimension through a stakeholder lens. *Corp. Soc. Responsib. Environ. Manag.* **2019**, *26*, 1135–1153. [CrossRef]
32. Walton, G.N. *Thermal Analysis Research Program Reference Manual*; NBSSIR 83-2655; National Bureau of Standards: Washington, DC, USA; National Engineering Lab., Department of Energy: Washington, DC, USA, 1983.
33. Clark, G.; Allen, C. The Estimation of Atmospheric Radiation for Clear and Cloudy Skies. In Proceedings of the 2nd National Passive Solar Conference (AS/ISES), Philadelphia , PA, USA, 16–18 March 1978; pp. 675–678.
34. Mirsadeghi, M.; Costola, D.; Blocken, B.; Hensen, J.L.M. Review of external covective heat transfer coefficient models in building energy simulation programs: Implementation and uncertainty. *Appl. Therm. Eng.* **2013**, *56*, 134–151. [CrossRef]
35. Hagishima, A.; Tanimoto, J. Field measurements for estimating the convective heat transfer coefficient at building surfaces. *Build. Environ.* **2003**, *38*, 873–881. [CrossRef]
36. American Society of Heating, Refrigerating and Air Conditioning Engineers Inc. *ASHRAE Fundamentals Handbook (S.I.)*; American Society of Heating, Refrigerating and Air Conditioning Engineers Inc.: Atlanta, GA, USA, 1997.
37. Sanjuan, C.; Suárez, M.J.; Blanco, E.; Heras, M.D.R. Development and experimental validation of a simulation model for open joint ventilated facades. *Energy Build.* **2011**, *43*, 3446–3456. [CrossRef]
38. Mastrapostoli, E.; Santamouris, M.; Kolokotsa, D.; Vassilis, P.; Venieri, D.; Gompakis, K. On the ageing of cool roofs: Measure of the optical degradation, chemical and biological analysis and assessment of the energy impact. *Energy Build.* **2016**, *114*, 191–199. [CrossRef]
39. Xue, X.; Yang, J.; Zhang, W.; Jiang, L.; Qua, J.; Xu, L.; Zhang, H.; Song, J.; Zhang, R.; Li, Y.; et al. The study of an energy efficient cool white roof coating based on styrene acrylate copolymer and cement for waterproofing purpose. Part I: Optical properties, estimated cooling effect and relevant properties after dirt and accelerated exposures. *Constr. Build. Mat.* **2015**, *98*, 176–184. [CrossRef]
40. Durability, Pausing for Reflection on Aging of the Cool Roof. Journal of Architect Coatings. June/July 2008. Available online: https://www.paintsquare.com/library/articles/Durability_Pausing_for_reflection_on_aging_of_the_cool_roof.pdf (accessed on 12 January 2020).
41. Bretz, S.E.; Akbari, H. Long-term performance of high-albedo roof coatings. *Energy Build.* **1997**, *25*, 159–167. [CrossRef]
42. Eilert, P. *High Albedo (Cool) Roofs: Codes and Standards Enhancement (CASE) Study*; Pacific Gas and Electric Company: San Francisco, CA, USA, 2000.
43. Prontuario de Soluciones Constructivas del CTE. Instituto de Ciencias de la Construcción Eduardo Torroja. Available online: http://cte-web.iccl.es/materiales.php (accessed on 12 March 2020).
44. Díaz, P.F. Centrales Térmicas. Biblioteca Sobre Ingeniería Energética. Universidad de Cantabria. Available online: https://pfernandezdiez.es/es/libro?id=15 (accessed on 15 March 2020).
45. Agencia Estatal de Meteorología de España. Guía Resumida del Clima en España (1981–2010). 2010. Available online: http://www.aemet.es/es/conocermas/recursos_en_linea/publicaciones_y_estudios/publicaciones/detalles/guia_resumida_2010 (accessed on 15 January 2020).
46. Auliac, S.; Le Hyaric, A.; Morice, J.; Hecht, F.; Ohtsuka, K.; Pironneau, O. FreeFem++. Third Edition, Version 3.31-2. Available online: http:www.freefem.orgr (accessed on 19 January 2020).

47. Energy Plus Software. U.S. Department of Energy (DOE). Building Technologies Office (BTO). Available online: https://energyplus.net/downloads (accessed on 19 January 2020).
48. Çengel, Y. *Heat and Mass Transfer. A Practical Approach*, 3rd ed.; McGraw Hill: New York, NY, USA, 2007.
49. Gentle, A.R.; Aguilar, J.L.C.; Smith, G.B. Optimized cool roofs: Integrating albedo and thermal emittance with R-value. *Sol. Energy Mater. Sol. Cells* **2011**, *95*, 3207–3215. [CrossRef]
50. Rossi, M.; Rocco, V.M. External walls design: The role of periodic thermal transmittance and internal areal heat capacity. *Energy Build.* **2014**, *68*, 732–740. [CrossRef]
51. Al-Sanea, S.A.; Zedan, M.F.; Al-Ajlan, S.A. Effect of electricity tariff on the optimum insulation-thickness in building walls as determined by a dynamic heat-transfer model. *Appl. Energy* **2005**, *82*, 313–330. [CrossRef]
52. Ozel, M. Effect of wall orientation on the optimum insulation thickness by using a dynamic method. *Appl. Energy* **2011**, *88*, 2429–2435. [CrossRef]
53. Daouas, N. Impact of external longwave radiation on optimum insulation thickness in Tunisian building roofs based on a dynamic analytical model. *Appl. Energy* **2016**, *177*, 136–148. [CrossRef]
54. Arumugam, R.S.; Garg, V.; Ram, V.V.; Bhatia, A. Optimizing roof insulation for roofs with high albedo coating and radiant barriers in India. *J. Build. Eng.* **2015**, *2*, 52–58. [CrossRef]
55. Synnefa, A.; Saliari, M.; Santamouris, M. Experimental and numerical assessment of the impact of increased roof reflectance on a school building in Athens. *Energy Build.* **2012**, *55*, 7–15. [CrossRef]
56. Reglamento de Instalaciones Térmicas en los Edificios. Ministerio para la Transición Ecológica y el Reto Demográfico. Available online: https://energia.gob.es/desarrollo/EficienciaEnergetica/RITE/Paginas/InstalacionesTermicas.aspx (accessed on 27 January 2020).
57. Duffie, J.A.; Beckman, W. *Solar Engineering of Thermal Processes*; John Wiley and Sons Inc.: Hoboken, NJ, USA, 2006.
58. CYPE Engineers. CYPE Ingenieros Construction Price Generator. 2017. Available online: http://generadorprecios.cype.es/(accessed on 28 March 2020).
59. Vincelas, F.F.C.; Ghislain, T.; Robert, T. Influence of the types of fuel and building material on energy savings into building in tropical region of Cameroon. *Appl. Therm. Eng.* **2017**, *122*, 806–819. [CrossRef]
60. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php/Natural-gas-price-statistics (accessed on 22 March 2020).
61. Nydahl, H.; Andersson, S.; Astrand, A.P.; Olofsson, T. Energy and Buildings Including future climate induced cost when assessing building refurbishment performance. *Energy Build.* **2019**, *203*, 109428. [CrossRef]
62. Commission Delegated Regulation (EU) No 626/2011 of 4 May 2011 Supplementing Directive 2010/30/EU of the European Parliament and of the Council with Regard to Energy Labelling of Air Conditioners. Available online: https://ec.europa.eu/info/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/energy-label-and-ecodesign/energy-efficient-products/air-conditioners-and-comfort-fans_en (accessed on 8 March 2020).
63. Kloepffer, W. Life cycle sustainability assessment of products. *Int. J. Life Cycle Assess.* **2008**, *13*, 89–95. [CrossRef]
64. Falcone, P.M.; Imbert, E. Social Life Cycle Approach as a Tool for Promoting the Market Uptake of Bio-Based Products from a Consumer Perspective. *Sustainability* **2018**, *10*, 1031. [CrossRef]