PROCEEDINGS OF ECOS 2026 - THE 39TH INTERNATIONAL CONFERENCE ON

EFFICIENCY, COST, OPTIMIZATION, SIMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS

28 JUNE – 03 JULY, 2026, CONSTANTA, ROMANIA

A MULTI-CRITERIA OPTIMIZATION FOR THE MAINTENANCE STRATEGIES OF COOL MATERIALS IN BUILDING ENVELOPES

Evangelos Vidalis[a], Konstantinos Polychronakis[a], Dimitrios Pallantzas[a], Angeliki Kitsopoulou[a], Dimitrios N. Korres[a], Evangelos Bellos[b], Christos Tzivanidis[a]

[a] Thermal Engineering Department, School of Mechanical Engineering, National Technical University of Athens, Athens, Greece, evanvidalis@mail.ntua.gr CA, polichronakis_konstantinos@mail.ntua.gr, d_pallantzas@mail.ntua.gr, akitsopoulou@mail.ntua.gr, korres@central.ntua.gr, ctzivan@central.ntua.gr
[b] Department of Mechanical Engineering, School of Engineering, University of West Attica, Athens, Greece, bellose@uniwa.gr

Abstract:

The building sector represents a major contributor to global energy consumption, while envelope performance plays a highly important role in determining thermal loads and cooling energy demand. With space cooling demand projected to increase significantly in the upcoming decades due to climate change and increased comfort expectations, passive envelope strategies aimed at reducing solar heat gains are investigated as effective means to improve energy efficiency and maintain appropriate indoor thermal conditions. Cool materials are widely applied as a passive solution due to their ability to reflect solar radiation and limit heat gains. However, their thermo-optical properties change over time as a result of aging and soiling, leading to a gradual decline in performance. This degradation creates uncertainty regarding the long-term effectiveness of cool coatings and raises the question of when re-painting should be performed from both an energy and economic perspective. This study investigates the maintenance strategies of cool materials as a multi-criteria optimization problem, aiming to identify optimal repainting intervals that balance energy performance, thermal comfort and life cycle cost. A detailed building energy model is developed in the environment of DesignBuilder to simulate the temporal evolution of surface reflectance and its restoration through the re-application of cool material coatings. The model is used to assess the impact of different re-painting strategies on annual and peak cooling demand, as well as on indoor thermal conditions under varying climatic and operational scenarios. Energy simulations are coupled with a life cycle economic assessment that accounts for maintenance costs and energy-related savings, enabling the evaluation of alternative strategies. Thermal comfort performance is assessed using appropriate comfort indices, the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD), in order to measure the influence of envelope degradation and maintenance actions on occupant conditions. The energy consumption has a variation of 63.8% depending on the repaint interval, while the PPD index's values are between 10.96% and 14.12% for all the time periods of each maintenance strategy. The life cycle cost for the optimum maintenance strategy regarding the repaint was calculated at 8512 €.

Keywords:

Cool materials; Solar reflectance; Ageing of cool materials; Roof; Thermal comfort; Optimization.

1. Introduction

The sector with the largest global annual energy consumption is the building sector and is responsible for about 36% of the final energy use and 40% of the energy-related CO_2 emissions according to recent reports by the International Energy Agency [1, 2]. One of the categories within the building sector that accounts for a large percentage of this energy consumption is space cooling, which, in the last decades, is one of the fastest-growing energy categories in buildings and is estimated to have tripled since 1990 [3]. In addition to that, the global cooling energy demand is expected to increase by at least 60% to 120% in the 2090s (in comparison with the 2010s), which is mostly a result of climate change, population growth and urbanization, as well as the continuously rising living standards [4]. Urbanization further affects the rising cooling energy demand by intensifying the so-called Urban Heat Island effect (UHI). This effect is attributed mainly to the replacement of natural land with dense, highly absorptive construction materials (like cement), which leads to elevated surface and air temperatures in urban areas in comparison to rural areas. Studies have shown that the urban temperatures can be 2–5°C higher on average, while the minimum COP (Coefficient of Performance) value of air conditioners may be decreased up to 25% [5, 6]. Additionally, the UHI effect can potentially result in an increase in the building cooling energy consumption by an average of 19%, varying from 10% up to120%, depending on the type of building and the geographic location [7]. The extended use of dark and low-reflectance materials in roofs and pavements, combined with limited vegetation, significantly contributes to this phenomenon [8]. As a result, buildings in urban environments are facing increased cooling loads, reduced energy efficiency, and worse indoor thermal conditions.

To tackle these challenges, among the most efficient strategies are the passive cooling strategies, which have gained increasing attention as cost-effective and sustainable solutions for improving building performance. Among these, cool materials have been widely recognized for their ability to reduce solar heat gains through the building envelope. These materials are characterized by high solar reflectance, which sometimes can be above 0.80 and high thermal emittance (0.9), allowing them to reflect a large fraction of solar radiation and faster release of absorbed heat in the form of infrared radiation [9]. Their application on building roofs and facades has been proven to reduce roof surface temperatures by up to 20°C under peak summer conditions, leading to significant reductions in cooling energy demand [10]. Moreover, cool roofs are capable of achieving cooling energy savings ranging from 10% to 40%, depending on climate conditions and building characteristics [11]. In addition to energy savings, cool materials can significantly improve indoor thermal comfort by reducing indoor air temperatures and mitigating overheating risks. At the urban scale, a wide implementation of cool materials with high reflectivity can also assist in mitigating the UHI effect, which further enhances their environmental benefits [12].

Despite their promising performance, the effectiveness of cool materials throughout their lifetime is highly affected by their exposure to environmental conditions. Over time, while the material is applied, the deposition of pollutants like dust and organic compounds, and biological contaminants, along with material aging, leads to a gradual degradation of their thermo-optical properties [13]. Thus, solar reflectance tends to decrease as surfaces become soiled, which results in increased solar absorptance and reduced cooling efficiency. Specifically, solar reflectance can decrease from initial values of approximately 0.80 to values as low as 0.50 within 5 years of lifetime, with a different rate and at a different scale depending on environmental conditions and material type [14]. The degradation of cool materials introduces uncertainty regarding their long-term energy performance and to tackle the issue, the correct maintenance strategies have to be examined. Maintenance actions, including cleaning or repainting, can restore the original properties of the material, though for cleaning, this can be limited to a specific percentage and not completely [15]. However, both of these interventions require additional costs, including material and labor expenses, which must be considered in any comprehensive evaluation. This highlights the importance of determining the optimal timing and frequency of maintenance actions, which represents a complex trade-off between energy savings and economic cost. On the one hand, frequent maintenance ensures that the material maintains high reflectance, which ensures minimizing cooling demand and improves indoor thermal comfort. On the other hand, from an economic perspective, frequent reapplication of the material increases life cycle costs and may reduce the overall cost-effectiveness of the solution. This trade-off highlights the necessity of adopting a multi-criteria approach that simultaneously considers energy performance, thermal comfort, and economic aspects. Levinson et al. (2005) conducted detailed outdoor exposure studies of roofing materials, documenting the decline of solar reflectance over time and its implications for building thermal loads [14]. Noelia et al. [15] examined the decrease of cool materials and found that throughout a period of 3 years, their ability to reduce urban temperatures was diminished by up to 40%. Similarly, Mastrapostoli et al. (2015) systematically analyzed the weatherization of the cool roofs in two buildings in Athens, Greece and measured and compared the optical properties of the aged, cleaned and new cool roofs, but did not integrate repainting or cleaning strategies into a life-cycle decision context [13]. De Masi et al. (2025) presented the results of a three-year experimental study in a Mediterranean climate regarding the effect of aging on aerogel and ceramic cool paints and the impact of cleaning their surface in restoring the solar reflectance of the material [16].

To address this gap, the present study investigates the maintenance strategies of cool materials as a multi-criteria optimization problem. A detailed building energy model is developed using DesignBuilder, which utilizes EnergyPlus as its simulation engine, to evaluate the impact of degradation and maintenance on building performance over time. The degradation of cool material properties is modeled through a time-dependent reduction in solar reflectance, while repainting actions are simulated as the restoration of the initial material properties. This work considers multiple scenarios with varying maintenance intervals (repaint period) to assess their influence on key performance indicators. Among them, energy performance is evaluated in terms of annual cooling demand and maximum cooling load, while indoor thermal comfort is addressed using the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) indices. Lastly, a life cycle cost analysis is conducted, incorporating both expenses due to energy consumption and maintenance costs, to enable a holistic economic evaluation of each scenario. By integrating energy, comfort, and economic criteria, this study aims to identify optimal maintenance strategies that balance energy performance and cost over a period of fifteen years. This work can contribute to a better understanding of the long-term behavior of cool materials and provide valuable insights for the development of effective and sustainable building retrofit strategies under increasing climate stress conditions.

2. Materials and methods

2.1. Building description

The examined building, which is presented in **Figure 1**, is a residential apartment with a total floor area of 100 m^2 and is located in the region of Athens, Greece. The building's envelope consists of a common masonry of brick and concrete, with a window-to-wall ratio of 30% for all the sides of the building, which are adjacent to the ambient. The building's thermal transmittance values are set according to the allowed values for the region of Athens, according to the Technical Chamber of Greece [17]. Specifically, for the external walls, the thermal transmittance (U-value) is 0.44 $W/(m^2 \cdot K)$, while for the windows it is 2.43 $W/(m^2 \cdot K)$, as shown in **Table 1**. The g-value is set to 0.67.

The apartment has a total of four occupants, with a specific load per each of 80 W [17], and the occupancy level of the building varies, with an average of 75%. Regarding the activity of the building, the lighting's daily factor has an average of 48% and the specific load is 3.5 W/m^2, while as for the appliances these values are 41% and 2.2 W/m^2 [17]. For the HVAC system, a reversible air-to-air heat pump is selected with a seasonal energy efficiency ratio of 4.5 for the summer period [18]. Finally, the uncontrolled introduction of outside air through the building elements (infiltration rate) is set to 0.4 ach [19].

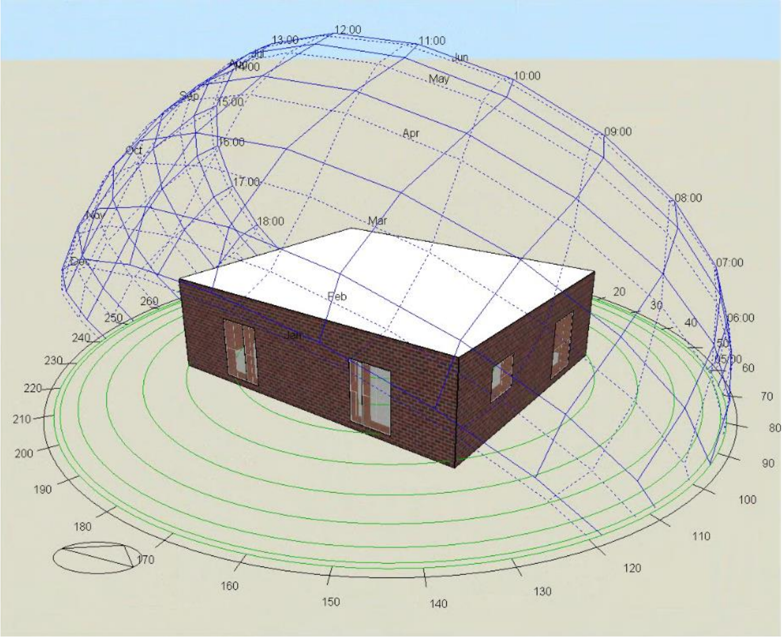

__Figure 1__. The examined building.

__Table 1__. Building Characteristics

Parameter	Value
U-value of walls $[W/(m^2 \cdot K)]$	0.44
U-value of roof [W/(m2·K)]	0.42
U-value of windows $[W/(m^2 \cdot K)]$	2.43
g-value	0.67
Specific load of lighting $[W/m^2]$	3.5
Specific load of appliances $[W/m^2]$	2.2
Infiltration rate [ach]	0.4
EER of the reversible air-to-air heat pump	4.5

2.2. Maintenance scenarios

On the roof of the building described above, a cool material was applied in all scenarios. Its initial thermo-optical properties are shown in **Table 2** below.

***Table 2**. Properties of the cool material (Data were derived from Ref. [15, 20])*

Parameter	Value
Specific Heat capacity [J/(kg·K)]	800
Conductivity [W/(m·K)]	1.4
Solar reflectance	0.83
Emissivity	0.9
Density [kg/m^3]	2100
Material thickness [cm]	1

Because of the exposure of the material to the environmental conditions, as described above, there will be a decrease in its energy efficiency (regarding cooling energy savings) and specifically the solar reflectance. The greatest decrease during the lifespan of the cool material is observed during the first year of service, and of that, more than half occurs during the first three months [21]. In addition to that, Mastrapostoli et al. (2015) measured a decrease of 33% after three years of service for a cool material that was applied on the roof of two school buildings in Athens, Greece [13]. In the later stages of aging, the annual decrease in solar reflectance is typically very limited, often remaining within a few percentage points per year. Based on these, the decrease in the solar reflectance, as well as the value of solar reflectance of the material, are shown in **Table 3** and **Figure 2** below.

***Table 3**. Properties of the cool material*

Year	Solar reflectance	Decrease in solar reflectance compared to initial properties [%]
0	0.83	-
1	0.67	20
2	0.59	28
3	0.55	33
4	0.53	36
5	0.52	38

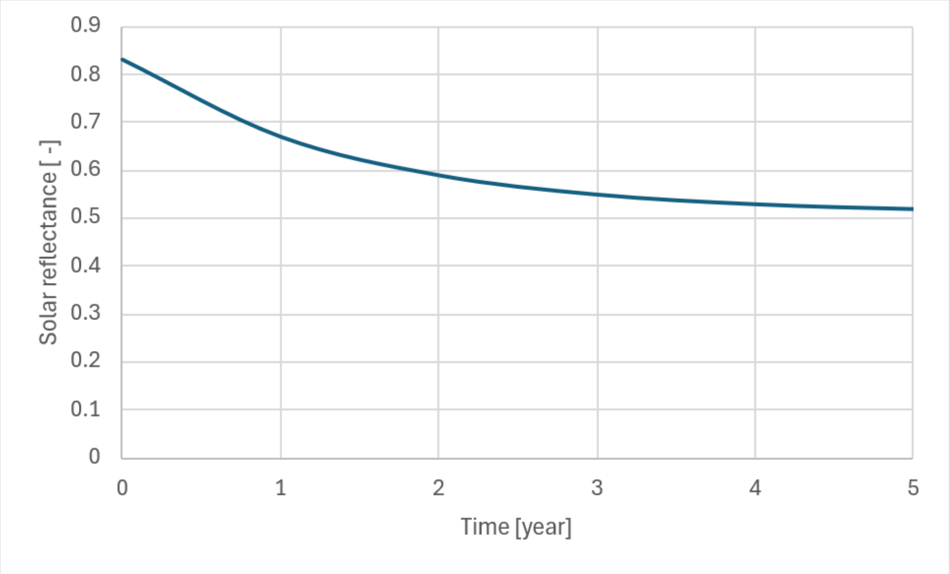

***Figure 2**. Decrease in the solar reflectance of the cool material during its lifespan.*

As for the maintenance strategies, the three scenarios examined in the present study include the repaint of the material every year, every three years and every five years, respectively. All scenarios were evaluated for a time period of fifteen years. At the time of the repaint, the solar reflection of the material is reset to its initial value. Regarding the cost of the material, it was taken into account that about two hundred to three hundred grams of material are required for every square meter of roof surface [22], and that the cost is 20 €/kg [23]. Finally, the labour cost is set to 200 € per repaint.

2.3. Simulation strategy

The energy performance analysis and thermal comfort calculations are carried out with the use of the DesignBuilder [24] software and the EnergyPlus simulation program [25]. The accuracy of the methodology followed in this study has been confirmed by previous studies [26 - 28]. In order to determine both indoor and outdoor convective heat transfer coefficients, the TARP algorithm is selected. For the climatic conditions, the analysis is carried out for the region of Athens, Greece [37°58′54″N, 23°43′51″E], with the use of weather data that are obtained from the DesignBuilder weather database.

2.4. Basic mathematical formulation part

The decrease of solar reflectance of the cool material is calculated as shown in **Eq. 1**, where t is the age of the material in [years], r_∞ is the long-term reflectance of the material, equal to 0.5, k_1 and k_2 are the degradation rate constant [year^{-1}] for the first year (1.2 year^{-1}) and the following years (0.25 year^{-1}) respectively [29, 30].

$$r(t) = r_\infty + 0.23 \cdot e^{-k_1 t} + 0.1 \cdot e^{-k_2 t} \qquad (1)$$

The predicted mean vote (PMV) is calculated as a deviation of an occupant's total energy loss (L), in [W/m^2], from its metabolic rate (M), in [W/m^2], according to the following equation [31]:

$$PMV = (0.303 \cdot e^{-0.036 \cdot M} + 0.028) \cdot (M - L) \qquad (2)$$

The thermal comfort equation is based on a steady-state regression analysis. Fanger's model mirrors thermal perception by measuring deviation from optimal comfort conditions. The Predicted Percentage of Dissatisfied (PPD) is computed as [31]:

$$PPD = 100 - 95 \cdot e^{(-0.03353 \cdot PMV^4 - 0.2179 \cdot PMV^2)} \qquad (3)$$

The metabolic rate for the occupants of the apartment is 58.1 W/m^2, while the value of the insulation of clothes is 1.0 clo or 0.2325 (m^2·K/W) for the colder months (winter period) and 0.5 clo or 0.0775 (m^2·K)/W for warmer months (summer period) [21].

The total cost for the repaint of the material (RC) is calculated based on **Eq. 4**, where MC is the material cost equal to 20 €/kg, A is the total surface of the roof in square meters and LC is the labour cost set to 200 € per repaint. The electricity price for residential use is considered equal to 0.14 €/kWh [32].

$$RC = 0.25 * A * MC + LC \qquad (4)$$

The total evaluation score (ES) of each maintenance strategy is calculated as shown in **Eq. 5**, based on its energy performance (ENP), economic performance (ECP) and thermal comfort (THC), each given a weighting factor as presented. As shown, the energy performance and economic performance are given a higher weighting factor since they directly influence both the operational efficiency and life-cycle cost of the building, being the primary decision-making criteria for the maintenance planning. Thermal comfort is given a lower but not insignificant weighting factor, as it is essential for the well-being of the occupants.

$$ES = 0.4 * ENP + 0.4 * ECP + 0.2 * THC \qquad (5)$$

Respectfully, the score of each category (CS) is calculated based on **Eq. 6**, where x is one of the sizes of Total Energy Consumption for the fifteen-year period, RC and PPD index. Max and min are the maximum and minimum values of the size x between the three different maintenance strategies.

$$CS = \frac{\max - x}{\max - min} \qquad (6)$$

3. Results and discussion

The present study focuses on a residential building with relatively high thermal performance characteristics, which are not met for buildings that are of a greater age and have not been energy retrofitted. The selection of this building has been made to isolate the impact of the examined maintenance strategies under controlled conditions, and it is acknowledged that in buildings with poorer thermal properties, the relative benefits of repainting of roof cooling materials are expected to be more pronounced, leading to greater energy savings and different performance rankings.

Firstly, the baseline is analyzed, in which the cool material has its initial properties, with a solar reflectance of 0.83. According to the calculations of the energy performance analysis, the cooling energy demand is 1506.67 kWh for a period of one year (summer period), while the maximum cooling load is 3283.61 W and was observed on July 18th at 14:00. As for the thermal comfort analysis, the average PPD for the summer period (1st of May to 30th of September) is calculated at 10.96%.

The effect of the decrease in the solar reflectance of the cool material throughout the years, on the energy performance and thermal comfort of the examined building is shown in **Figure 3**. The greatest decrease in performance is observed during the first years, as expected, since during this time the effect of the environmental conditions on the solar reflectance of the material is greater. The increase of the PPD index is 28.8% after 5 years of service, while the increase of the maximum cooling load is 28.3% for the same amount of time. The increase in thermal discomfort and the cooling load follow the same pattern in relation to the decrease in the solar reflectance of the cool material, as expected.

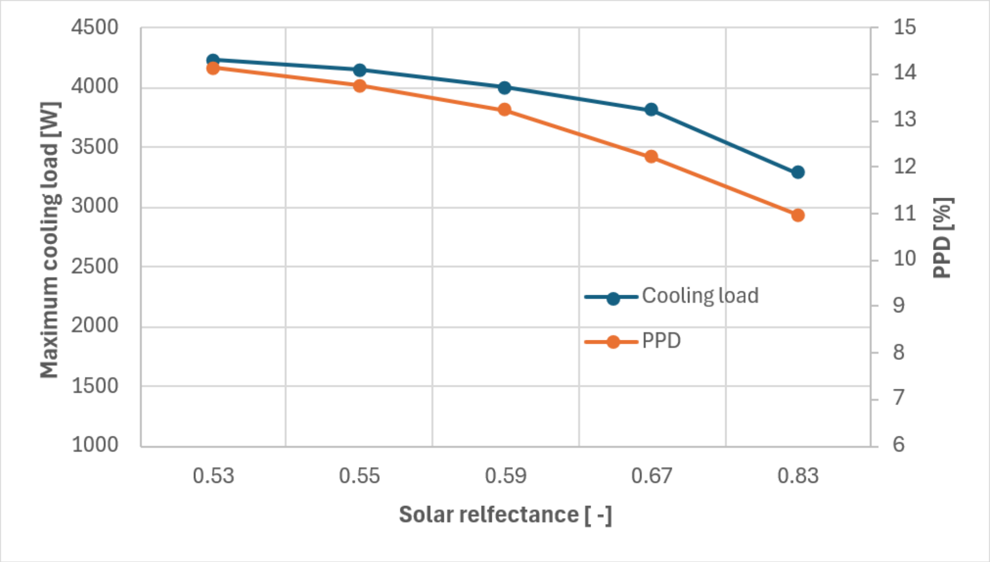

***Figure 3**. The effect of the decrease in the solar reflectance of the cool material on the maximum cooling load and the PPD index.*

The three maintenance strategies (repaint scenarios) regarding thermal comfort, energy performance and economic performance are investigated. The first scenario includes the repaint of the material every year before the summer period, while the second and third scenarios are the repaint after three and five years, respectively. The total cost for each repaint is calculated at 800 €. According to **Figure 4,** the total cooling energy during a period of fifteen years is 22,600 kWh for the first scenario, where the repaint is performed every year, while it is 37,031 kWh for the third scenario, where the repaint is performed every five years, 63.8% higher. For the second scenario, when the repaint is performed every 3 years, the total cooling energy consumption for the fifteen-year period is calculated at 32,233 kWh, 42.6% higher than the first scenario.

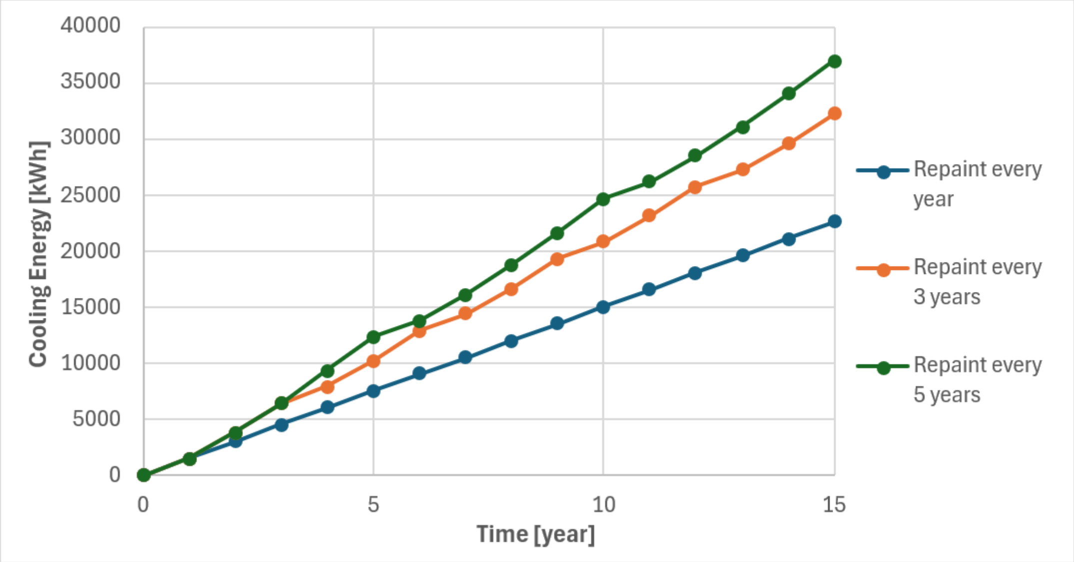

***Figure 4**. Cumulative cooling energy consumption through the fifteen-year period for each maintenance strategy.*

Regarding the thermal comfort, according to **Figure 5**, in all maintenance strategies, the average annual PMV values are between 0.5 and 0.8, indicating slightly warm conditions, while, as expected, they are lower when the cool material is repainted every year. As shown in **Figure 6**, the average annual value of the PPD index varies between 10.96% and 14.12%, depending on the age of the cool material as described in **Figure 3** above. The higher values in both diagrams, correspond to the last year before repainting of the cool material in each scenario, while, as described above, the increase of the indices of PMV and PPD (and so the decrease of the thermal comfort) is greater during the first and second year of the material's lifetime, reflecting the decrease of the cool material's solar reflectance. The increase of the average annual PPD index after one year of service of the cool material is 11.4 % compared to the value of the PPD index for the initial solar reflectance of the cool material, while there is only a 2.6% increase for the average annual PPD value during the fifth year of service compared to the one of the fourth year of service of the cool material.

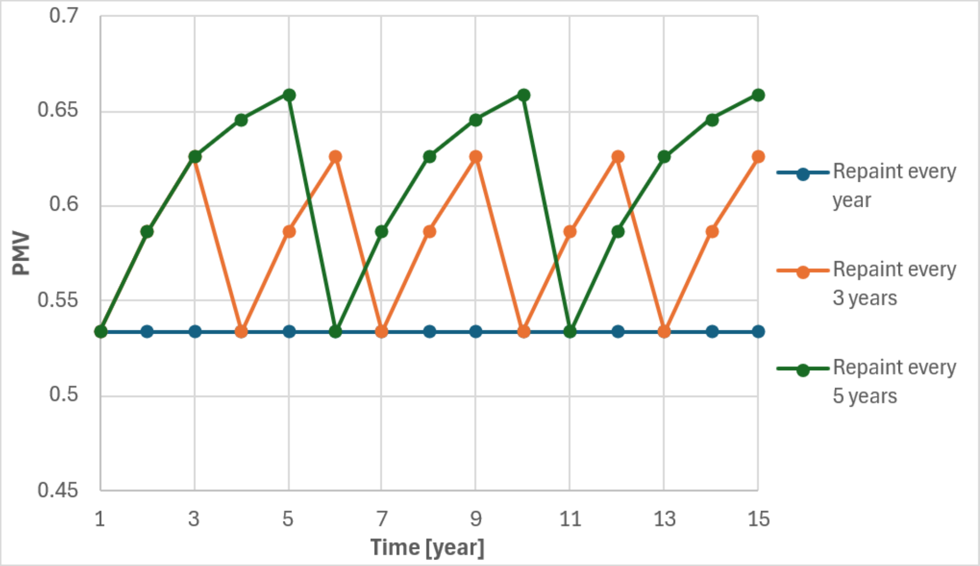

Figure 5. *PMV index through the fifteen-year period for each maintenance strategy.*

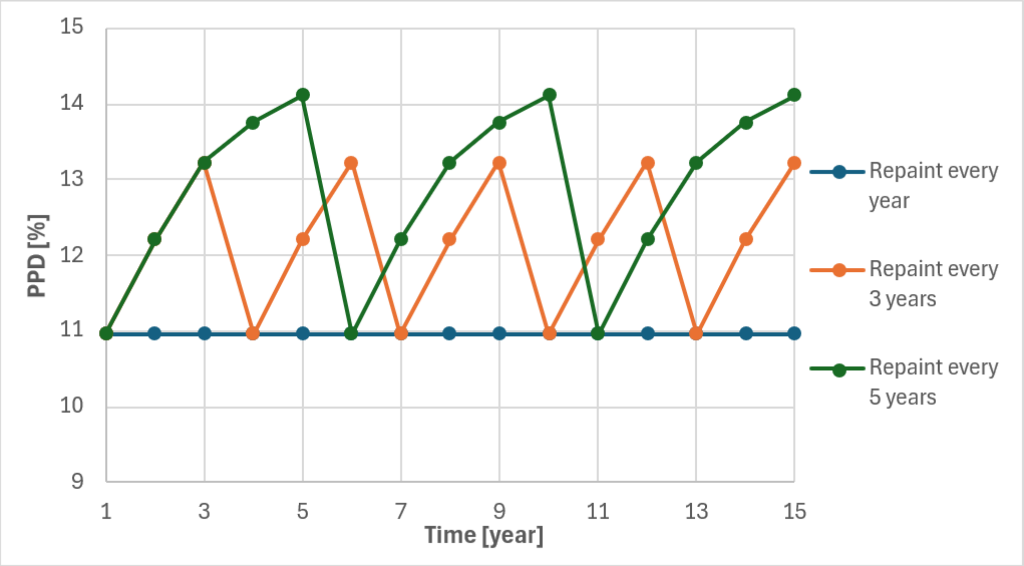

Figure 6. *PPD index through the fifteen-year period for each maintenance strategy.*

As it is presented in **Figure 7**, the energy cost is greater for the scenario where the repaint is performed every five years, calculated at 5184.38 € for the time period of fifteen years, compared to the one of 3164.01 € for the scenario where the repaint is performed every year (more than 60% higher). The increase in the energy cost is more than 50% after one year of service of the cool material, while the difference between the fourth and the fifth year of service is only about 5%, which shows that as time progresses, the rate of decrease of the energy performance of the cool material slows significantly.

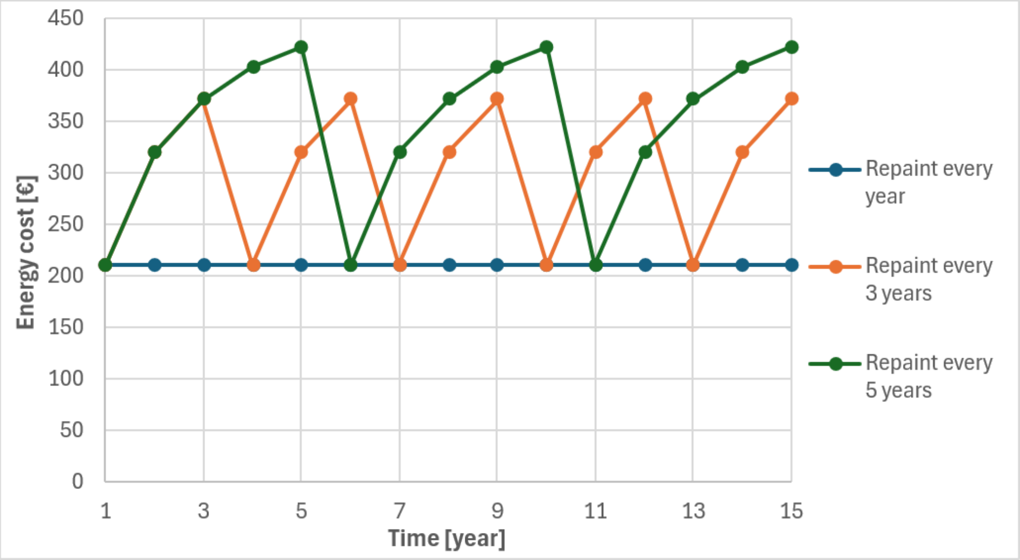

Figure 7*. Energy cost through the fifteen-year period for each maintenance strategy.*

The total cost, including both the energy cost as well as the repaint cost, as shown in **Figure 8**, is calculated at 15,164 €, 8512 € and 7584 € for each scenario, respectively, where the higher cost is for the repaints with the higher frequency. As it is presented, the difference in the total cost between the one-year repainting interval and the three-year repainting interval is significantly greater than the difference between the three-year repainting interval and the five-year repainting interval. This highlights the fact that the maintenance cost is of higher importance regarding the total cost, particularly when the repaintings are regular, while there is a greater balance when the repainting of the cool material is not that often.

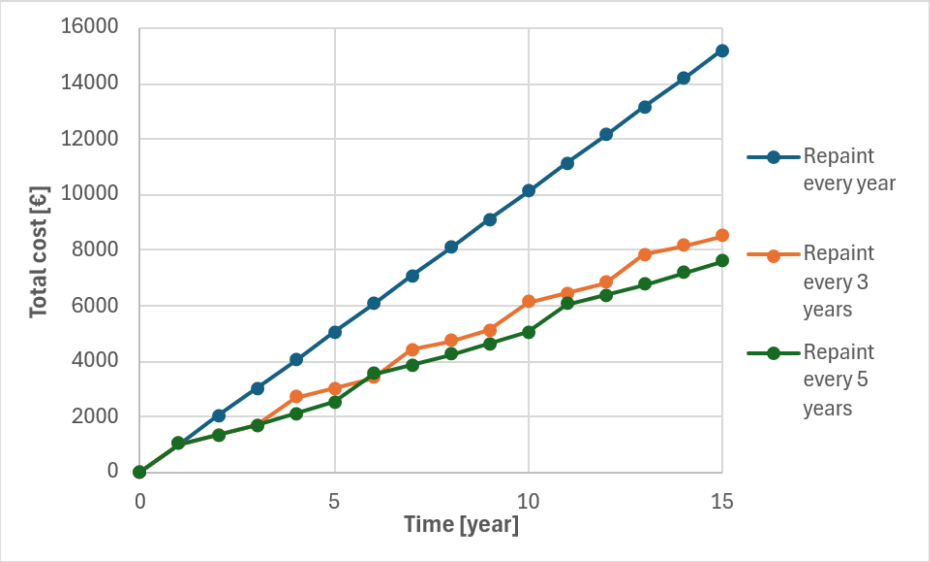

Figure 8*. Total cost through the fifteen-year period for each maintenance strategy.*

Finally, the comparison of the three maintenance strategies is presented in **Figure 7**. As shown, every strategy is evaluated based on its energy performance, economic performance and thermal comfort. Then, given a weighting factor of 0.4, 0.4 and 0.2, respectively, the total score of each strategy is calculated and presented. Regarding the thermal comfort and the energy performance, these two categories are better addressed through the one-year repaint interval, while on the opposite hand, as for the economic performance, the greatest score is achieved by the five-year repaint interval, indicating once again the fact that the repaint cost is of higher importance regarding the total cost. The highest score is the one of the strategy where repaint is performed every three years and combines relatively lower costs compared to the strategy where repaint is performed every year and better energy performance compared to the strategy where repaint is performed every five years, as shown in **Figure 9**.

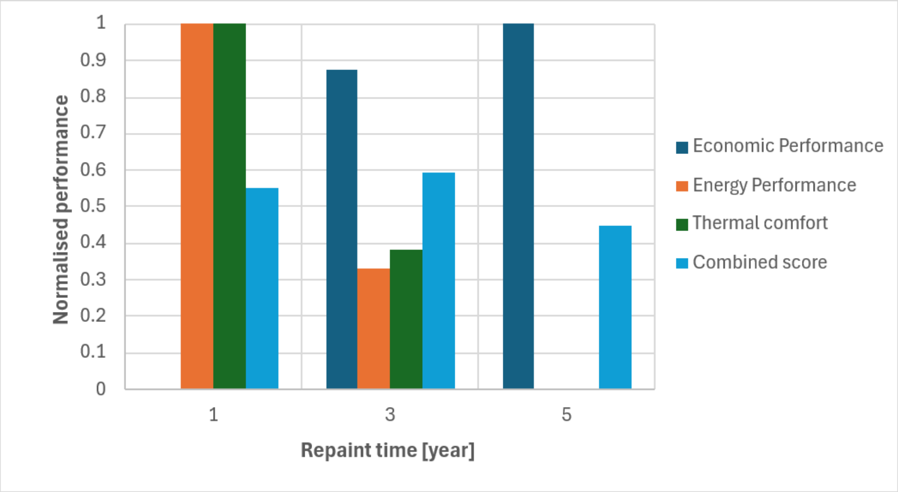

***Figure 9**. Evaluation of the performance for each maintenance strategy.*

4. Conclusions

In this study, the performance of cool materials applied to the roof of a residential apartment in Athens was investigated, regarding the energy consumption and the thermal comfort. Moreover, the evaluation of three different maintenance (repaint) strategies was performed, including the calculation of the life cycle cost for each one. The results showed that the 38% decrease in the solar reflectance of the cool material after a service of five years can result in an increase of 28% of the maximum cooling load and a 23% increase in the PMV index. Most of this increase was calculated during the first two years of the material's lifetime.

Regarding the maintenance strategies, three different repaint intervals were examined, including the repaint of the cool material every year, every three years and every five years. These were evaluated based on their energy and economic performance, as well as thermal comfort, to ensure a holistic approach. While the scenario that the repaint of the cool material is performed every year had a better energy performance, with a total cooling energy consumption of 22,600 kWh for the period of fifteen years, 61% lower than the one of the scenarios that the repaint is performed only once every five years. On the other hand, though, the total life cost was almost 100% more, mainly because of the high cost of the material.

After the energy performance, economic performance and thermal comfort were each given a weighting factor, the evaluation for the three strategies was performed. The optimal scenario is the one in which the repaint of the material is performed every three years. The total energy consumption for this maintenance strategy is 32,233.3 kWh, while the life cycle cost for the period of fifteen years is 8512.6 €. Finally, regarding thermal comfort, the average PPD index for the fifteen-year period is calculated at 12.13%.

In the future, it will be useful to conduct a study regarding the maintenance strategies and the ideal repaint interval of the thermochromic materials, since the ageing factor is significantly different. Additionally, there could be an investigation into the effect of future climate data on the performance and ageing of the cool materials, as well as their maintenance strategies. Finally, it would be essential to investigate the performance and ageing of the cool materials when applied on a larger (urban) scale.

Nomenclature

A	Area, m^2
g	Solar Heat Gain Coefficient
k	Degradation rate constant, year^{-1}
L	Total energy loss per occupant, W/m^2
LC	Labor Cost, €
M	Metabolic rate, W/m^2
MC	Maintenance cost, €
PMV	Predicted mean vote, -
PPD	Predicted percentage of dissatisfied, %
r	Solar reflectance of cool material
RC	Total cost for the repaint of the material, €
t	Time, years
U	Thermal transmittance, W/(m^2·K)

Abbreviations

ECP	Economic Performance
EER	Energy Efficiency Ratio
ENP	Energy Performance
ES	Evaluation Score
COP	Coefficient of Performance
THC	Thermal Comfort

Acknowledgements

This work has been carried out in the framework of the project NEW-EPOCH (eNErgy Waste solutions through development of POsitive sChool buildings as sustainable, innovative Hubs for community engagement) co-funded by the European Urban Initiative (Project Number: EUI03-242).

References

1. Zarco-Soto, F.J.; Zarco-Soto, I.M.; Ali, S.S.S.; Zarco-Periñán, P.J. Energy Consumption in Buildings: A Compilation of Current Studies. Energy Reports 2025, 13, 1293–1307, doi:10.1016/j.egyr.2024.12.069.
2. Zarco-Periñán, P.J.; Zarco-Soto, F.J.; Zarco-Soto, I.M.; Martínez-Ramos, J.L.; Sánchez-Durán, R. CO2 Emissions in Buildings: A Synopsis of Current Studies. Energies 2022, 15, 6635, doi:10.3390/en15186635.
3. Mastrucci, A.; Byers, E.; Pachauri, S.; Rao, N.D. Improving the SDG Energy Poverty Targets: Residential Cooling Needs in the Global South. Energy and Buildings 2019, 186, 405–415, doi:10.1016/j.enbuild.2019.01.015.
4. Elnagar, E.; Gendebien, S.; Georges, E.; Berardi, U.; Doutreloup, S.; Lemort, V. Framework to Assess Climate Change Impact on Heating and Cooling Energy Demands in Building Stock: A Case Study of Belgium in 2050 and 2100. Energy and Buildings 2023, 298, 113547, doi:10.1016/j.enbuild.2023.113547.
5. Salvati, A.; Coch Roura, H.; Cecere, C. Assessing the Urban Heat Island and Its Energy Impact on Residential Buildings in Mediterranean Climate: Barcelona Case Study. Energy and Buildings 2017, 146, 38–54, doi:10.1016/j.enbuild.2017.04.025.
6. Santamouris, M.; Papanikolaou, N.; Livada, I.; Koronakis, I.; Georgakis, C.; Argiriou, A.; Assimakopoulos, D.N. On the Impact of Urban Climate on the Energy Consumption of Buildings. Solar Energy 2001, 70, 201–216, doi:10.1016/S0038-092X(00)00095-5.
7. Li, X.; Zhou, Y.; Yu, S.; Jia, G.; Li, H.; Li, W. Urban Heat Island Impacts on Building Energy Consumption: A Review of Approaches and Findings. Energy 2019, 174, 407–419, doi:10.1016/j.energy.2019.02.183.
8. Akbari, H.; Pomerantz, M.; Taha, H. Cool Surfaces and Shade Trees to Reduce Energy Use and Improve Air Quality in Urban Areas. Solar Energy 2001, 70, 295–310, doi:10.1016/S0038-092X(00)00089-X.
9. Rawat, M.; Singh, R.N. A Study on the Comparative Review of Cool Roof Thermal Performance in Various Regions. Energy and Built Environment 2022, 3, 327–347, doi:10.1016/j.enbenv.2021.03.001.
10. Lee, S.; Cho, Y.-I.; Lee, M.-J.; Lim, Y.-S. The Evaluation of the Temperature Reduction Effects of Cool Roofs and Cool Pavements as Urban Heatwave Mitigation Strategies. Applied Sciences 2023, 13, 11451, doi:10.3390/app132011451.
11. Bamdad, K. Cool Roofs: A Climate Change Mitigation and Adaptation Strategy for Residential Buildings. Building and Environment 2023, 236, 110271, doi:10.1016/j.buildenv.2023.110271.
12. Santamouris, M. Cooling the Cities – A Review of Reflective and Green Roof Mitigation Technologies to Fight Heat Island and Improve Comfort in Urban Environments. Solar Energy 2014, 103, 682–703, doi:10.1016/j.solener.2012.07.003.
13. 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 and Buildings 2016, 114, 191–199, doi:10.1016/j.enbuild.2015.05.030.
14. Levinson, R.; Berdahl, P.; Asefawberhe, A.; Akbari, H. Effects of Soiling and Cleaning on the Reflectance and Solar Heat Gain of a Light-Colored Roofing Membrane. Atmospheric Environment 2005, 39, 7807–7824, doi:10.1016/j.atmosenv.2005.08.037.
15. Noelia, A.; Erica, C.; Alicia, C.M. Urban Passive Cooling. Aging Effects on Optical Properties of Roof Tiles. Energy Procedia 2014, 57, 3181–3190, doi:10.1016/j.egypro.2015.06.068.
16. De Masi, R.F.; Festa, V.; Ruggiero, S.; Russo, A.; Villano, F. Aging, Soiling, and Cleaning Effects on Cool Roof Performance: Experimental Insights on Aerogel-Based and Conventional Reflective

Coatings in Mediterranean Climate. Journal of Building Engineering 2025, 116, 114577, doi:10.1016/j.jobe.2025.114577.

17. Technical Guidelines of Technical Chamber of Greece (TEE); Athens, Greece, 2020.
18. “FTXM-R | Daikin.” Daikin.gr, 2022, www.daikin.gr/el_gr/products/product.html/FTXM-R.html.
19. Kitsopoulou, A.; Ziozas, N.; Iliadis, P.; Bellos, E.; Tzivanidis, C.; Nikolopoulos, N. Energy Performance Analysis of Alternative Building Retrofit Interventions for the Four Climatic Zones of Greece. Journal of Building Engineering 2024, 87, 109015, doi:10.1016/j.jobe.2024.109015.
20. Dabaieh, M.; Wanas, O.; Hegazy, M.A.; Johansson, E. Reducing Cooling Demands in a Hot Dry Climate: A Simulation Study for Non-Insulated Passive Cool Roof Thermal Performance in Residential Buildings. Energy and Buildings 2015, 89, 142–152, doi:10.1016/j.enbuild.2014.12.034.
21. Kültür, S.; Türkeri, N. Assessment of Long Term Solar Reflectance Performance of Roof Coverings Measured in Laboratory and in Field. Building and Environment 2012, 48, 164–172, doi:10.1016/j.buildenv.2011.09.004.
22. “ANTITHERM.” Sts.gr, 19 July 2023, sts.gr/proionta-ipiresies/antitherm.
23. “Price List of Products.” Sts.gr, 7 Sept. 2024, sts.gr/proionta-ipiresies/price-list/.
24. DesignBuilder Software Ltd. “DesignBuilder Software Ltd - Home.” Designbuilder.co.uk, 2019, designbuilder.co.uk/.
25. EnergyPlus. “EnergyPlus | EnergyPlus.” Energyplus.net, 2019, energyplus.net/.
26. Kitsopoulou, A.; Pallantzas, D.; Sammoutos, C.; Lykas, P.; Bellos, E.; Vrachopoulos, M.Gr.; Tzivanidis, C. A Comparative Investigation of Building Rooftop Retrofit Actions Using an Energy and Computer Fluid Dynamics Approach. Energy and Buildings 2024, 315, 114326, doi:10.1016/j.enbuild.2024.114326.
27. Kitsopoulou, A.; Bellos, E.; Lykas, P.; Vrachopoulos, M.Gr.; Tzivanidis, C. Multi-Objective Evaluation of Different Retrofitting Scenarios for a Typical Greek Building. Sustainable Energy Technologies and Assessments 2023, 57, 103156, doi:10.1016/j.seta.2023.103156.
28. Kitsopoulou, A.; Bellos, E.; Lykas, P.; Sammoutos, C.; Vrachopoulos, M.Gr.; Tzivanidis, C. A Systematic Analysis of Phase Change Material and Optically Advanced Roof Coatings Integration for Athenian Climatic Conditions. Energies 2023, 16, 7521, doi:10.3390/en16227521.
29. Sleiman, M.; Kirchstetter, T.W.; Berdahl, P.; Gilbert, H.E.; Quelen, S.; Marlot, L.; Preble, C.V.; Chen, S.; Montalbano, A.; Rosseler, O.; et al. Soiling of Building Envelope Surfaces and Its Effect on Solar Reflectance – Part II: Development of an Accelerated Aging Method for Roofing Materials. Solar Energy Materials and Solar Cells 2014, 122, 271–281, doi:10.1016/j.solmat.2013.11.028.
30. Berdahl, P.; Akbari, H.; Levinson, R.; Miller, W.A. Weathering of Roofing Materials – An Overview. Construction and Building Materials 2008, 22, 423–433, doi:10.1016/j.conbuildmat.2006.10.015.
31. Omidvar, A.; Kim, J. Modification of Sweat Evaporative Heat Loss in the PMV/PPD Model to Improve Thermal Comfort Prediction in Warm Climates. Building and Environment 2020, 176, 106868, doi:10.1016/j.buildenv.2020.106868.
32. “Electricity Prices in Greece.” Euenergy.live, 2026, euenergy.live/country.php?a2=GR.