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The Effect of Solar Control Films on Enhancing the Energy Efficiency of Historic Buildings

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Abstract

The use of solar control foils (SCFs) is a minimally invasive method that enables energy savings while preserving the original character of historic building facades. This study analysed the energy reduction potential of four types of window films applied to single-pane glazing. A typical office space at the University of Bologna, located in a historic building, served as a case study. Building performance simulations using DesignBuilder and Berkeley Lab Optics software were applied as research tools. The potential reduction in cooling energy consumption by using SCFs can be up to about 35% in humid subtropical (Bologna) and Mediterranean (Seville) climates. A decrease of about 53% can be achieved in a temperate oceanic climate (Paris). Due to the reduction in heat gains from solar radiation, there is an increase in energy consumption for heating by 6% to even 50% and up to a maximum of about 15% for artificial lighting. Financial indicators such as LCC, NPV, and IRR were used to select the optimal option. The recommended solution was an SCF installed on the inside of the window with SHGC of 0.452, a visible transmittance of 0.361, and an inside reflectance of 0.195. Additionally, this study proposes a method for correcting heating and cooling energy demand results calculated based on data for a typical meteorological year and weather parameters measured over the past 19 years. This allows for the validity of energy simulation results by taking into account current climate changes.

Keywords: solar control foils; historical building; single-pane glazing; solar heat gains; energy consumption; cooling; heating

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1. Introduction

Improving the energy efficiency of historic buildings is a critical undertaking that can lead to reduced energy consumption and, in turn, lower operating costs. Moreover, the renovation of old building stock fits perfectly into the strategy of decarbonisation and climate change mitigation. Energy performance modernisation can also improve the quality of the indoor environment by reducing overheating in summer and underheating in winter, and by reducing moisture problems and large radiation temperature gradients in partitions. However, integrating energy-saving technologies while preserving cultural heritage is a difficult and complex task. Typically, each historic building requires an individual analysis to select the optimal renovation method. In particular, traditional methods of thermal insulation of facades, replacement of roof coverings and the use of modern windows often encounter complications with obtaining secure heritage approvals. Another important aspect is the use of monitoring basic parameters of the internal environment to protect against building degradation.

Windows are an important architectural element that emphasises the historic character of old buildings. Single-glazed windows are often installed in old, historic buildings. The frames are made of steel or wood with decorative details. The panes are made of various types of glass, ranging from ordinary, thin and transparent to thick, so-called cathedral glass. The glazing surfaces are not usually large because the window is divided by vertical and horizontal muntins. Significant leaks often characterise windows of this type. This results in increased air infiltration, primarily due to the lack of seals and the misalignment of the window frame. Another disadvantage of single-glazed windows is the low resistance to rain or snow. Additionally, very low thermal resistance leads to significant heat losses in regions with a cold climate. In the summer, this type of glazing causes excessive solar heat gains (SHG).

Replacing with modern double- and triple-glazed constructions in historic buildings is often impossible due to regulations related to the conservation of monuments.

The use of foil glued to the surface of the glass is the simplest way to reduce the last-mentioned shortcomings of single-glazed windows.

These types of films can realise various functions, depending on their optical characteristics. The most popular are reflective films, which reflect solar radiation to limit solar gain by about 50 to even 80% and protect against UV radiation. Darkening films can decrease the amount of visible light that passes through a window. Low-emission (Low-E) foils are used to reduce heat transfer from inside the room through radiation. The main advantages of this solution are lower energy demand and improved thermal comfort.

Furthermore, films can be used for burglary protection (security function), noise reduction, and decorative purposes. However, these applications are beyond the scope of this article.

According to the European Window Film Association (EWFA), the concept of using films attached to window surfaces dates back to the early 1960s. These were relatively simple solutions designed to reflect solar radiation from the window.

Currently, window films are usually made using advanced technologies such as nanoparticle pigmentation, sputtering and vacuum metallization [1]. Ceramic window films are a recent technological advancement. The advantages of this type of film include high resistance to damage and almost complete UV radiation blocking [2].

Pereira et al. [2] conducted a comprehensive review of research related to determining the impact of SCF on building energy performance and thermal comfort. This study included numerical simulations, economic analyses, and experimental studies. Identifying areas requiring further research related to the impact of filters used to control solar radiation intensity was the primary goal of this article. The review revealed that while solar control films have been extensively studied in various climatic conditions, certain aspects still require further investigation.

The energy performance of solar control films has been evaluated through numerous experimental and simulation studies. Bahadori-Jahromi et al. [3] assessed the impact of solar films on total energy consumption in the four-story Hilton Hotel in Reading (UK). Their results indicated that SCFs reduce the annual energy demand for cooling by 35% but increase the energy demand for heating by 2%. Wang et al. [4] tested solar control films in Guangzhou (China) using an experimental platform for studying urban thermal environments [5], finding that unidirectional fluoroscopy grey film can reduce the air temperature in the occupied space by approximately 4 °C. Xamán et al. [6] performed numerical simulations showing that the use of SCF reduced solar gain by approximately

62% compared to the case without the filter on the warmest day, though it had practically no effect on the average temperature inside the room during winter conditions.

The location of film installation significantly affects performance, as demonstrated by Teixeira et al. [7], who experimentally evaluated double-glazed windows with and without SCF in three office spaces in Lisbon (Portugal). The analysis showed that SCFs installed on the exterior showed the best efficiency, reducing the air temperature inside the office by 6.9 °C and 2.3 °C during the cooling and heating periods, respectively. Installing SCFs on the interior window surface proved ineffective, only contributing to an increase in the greenhouse effect in the test room. Li et al. [8] studied the reduction in cooling demand and visible light in office buildings located in Hong Kong, showing that solar foil reduced the amount of solar energy reaching the office interior by approximately 30%, with visible light transmission reduced by approximately 76%.

The impact of SCFs on natural lighting conditions has also been investigated. Calama-González et al. [9] studied the effect of SFC on natural lighting levels in the University Hospital in Seville (Spain), determining a 12.2% reduction in electricity consumption for artificial lighting as a result of using SFC. Pereira et al. [10] evaluated the effect of different solar control films installed on single 6 mm thick glass panes at the Instituto Superior Técnico building in Lisbon (Portugal). The study results confirmed the significant impact of SCFs on reducing daylight levels below the critical glare threshold (3 klx) in the summer. However, the effectiveness of these films was negligible in the winter. Complementing these experimental findings, thermal modelling studies by Noh-Pat et al. [11] and Chaiyapinunt et al. [12] further demonstrated that optimal design parameters, such as the distance between glass panes and film positioning, can significantly enhance the performance of glazing systems with solar control coatings.

Several studies have combined experimental measurements with energy simulations to provide more comprehensive assessments. Moretti and Belloni [13] estimated the consumption of thermal and electrical energy in two adjacent offices at the University of Perugia in Perugia (Italy). The comparative analysis showed that SCFs reduced solar gain by approximately 60%, and the internal air temperature in the room with window film was 2 °C to 3 °C lower in the spring. The use of SFC allowed for a reduction in the demand for cooling energy by approximately 29% and caused an increase in the demand for heating energy by approximately 15%. Pereira et al. [14] determined the optical and thermal parameters of single-glazed windows with internally mounted SCF and Venetian blinds in two similar offices in Lisbon (Portugal). These studies showed that the use of SCFs reduced the average temperature inside the office by 14.7% in summer and by 7.1% in winter compared to a reference office without filters. Furthermore, low-emission filters have been found to reduce cooling energy demand by up to 86%. Unfortunately, an increase in energy demand for heating and lighting has been observed during the winter.

Teixeira et al. [15] evaluated the impact of different types of SCF on thermal comfort and energy efficiency in three identical office buildings located on the university campus of the Instituto Superior Tecnico in Lisbon (Portugal). The results of the experimental tests were used to calibrate the office space model developed in the EnergyPlus software environment. It was estimated that the highest thermal and optical efficiency was achieved by a film with a visible transmittance of 0.16 and a solar heat gain coefficient (SHGC) of 0.15, as it ensured thermal comfort for over 41% of office hours. The greatest reduction in annual energy consumption, by 38%, was achieved by a film with a visible transmittance of 0.63% and SHGC of 0.15.

Despite extensive research on SCF energy performance, economic analyses considering the full life cycle of window films remain limited. Pereira et al. [2] noted that this represents one of the most significant research gaps related to this topic. Pereira et al. [16] conducted one of the few comprehensive life cycle analyses, testing three types of SCFs. The spectrally selective film proved to be the best solution for retrofitting an existing glazing system, considering its life cycle energy (LCE) and carbon footprint. The retrofit option, which involved replacing existing windows, was the least effective, with an LCE 1.5 times higher than the options using window films. The effectiveness of solar foil in a single-family building in Kuwait was assessed by Al-Taqi et al. [17]. The foil used for theoretical analysis blocked 65% of solar radiation, and its visible light transmittance was 73%. It was estimated that the SCF installation reduced peak cooling demand by 6.7%, resulting in a 4.7% decrease in electricity consumption. A simple financial analysis based on the payback period was performed. The investment turned out to be unprofitable because the payback period was over 40 years, which is more than twice the lifespan of the SCF. Chan et al. [18] analysed the use of solar films in hotel buildings located in southern China, providing data on the energy efficiency of SCFs and their economic viability. The calculation results showed that the payback period for installing window filters was between 3.5 and 4.7 years. Hui and Kwok [19] evaluated the effect of using thin window films on energy consumption in office buildings in Hong Kong's climatic conditions. Simple payback periods were used to evaluate the effectiveness of using different kinds of SCFs on three types of glazing. The lowest SPBT values ranged from 2 to 5 years for films applied to standard clear glass. The longest payback periods, ranging from 12 to 38 years, were for low-emissivity windows. However, the authors of this study noted that life-cycle analysis would be necessary to select the optimal solution.

As can be seen from the above review of research works, practically only one study [16] has thoroughly analysed window films from a financial perspective, taking into account their life cycle. It should also be added that only two studies [10,14] comprehensively analysed the issue of installing SCFs on single-pane windows. However, no publications were found that addressed the renovation of single-pane glazing using window films in historic buildings. This represents a significant gap in the literature, as historic buildings with single-pane windows face unique challenges related to conservation regulations and the need to preserve original architectural character.

The strength of this study is its comprehensive approach, both energy- and financially wise, to the topic of glazing system modernisation in historic buildings. To generalise the conclusions, this issue was analysed for various locations with different climatic conditions. Furthermore, window filters with different characteristics, installed inside and outside the window, were considered. Additionally, taking into account climate change, a method for correcting energy demand for heating and cooling based on meteorological data from the last 19 years was proposed. Financial indicators such as LCC, NPV, and IRR were used to select the optimal solution for historic building renovation while preserving their architectural character.

2. Materials and Methods

The research described in this article was based primarily on energy simulations performed using the multiply validated Design Builder version 6.1.8.021 software. This tool performs energy and mass balances for both the building and its HVAC systems using the EnergyPlus [20] computational engine implemented within this software developed by the U.S. Department of Energy. The optical and thermal properties of the SCFs were determined using Optics 6.0. Basic financial indicators such as Life Cycle Costing (LCC), Net Present Value (NPV), and Internal Rate of Return (IRR) were used in the economic analysis. Additionally, a realistic scenario involving a 2% increase in energy prices was considered.

2.1. Description of the Room Selected for the Case Study

A typical room for university research staff (Figure 1) was chosen for this study approach. It is located on the first floor of the University of Bologna building at Viale Risorgimento 2, Bologna (Italy). The building was designed in the modernist style and put into use in 1935. The reference office is 4.24 m high and measures 4.73 m by 5.03 m. A 13.1 m^2 window occupies the southeast wall, while a 7.5 m^2 window occupies the northwest wall. This space is designed to accommodate four scientists.

Figure 1. Department of Industrial Engineering building, University of Bologna (taken by G. Semprini).

2.2. Assumptions for Developing the Computational Model

The 3D model of the case study office (Figure 2) was created in the DesignBuilder v.6.1.8 software. Two exterior walls participated in heat exchange. The remaining two walls, the ceiling and the roof were assumed to be adiabatic.

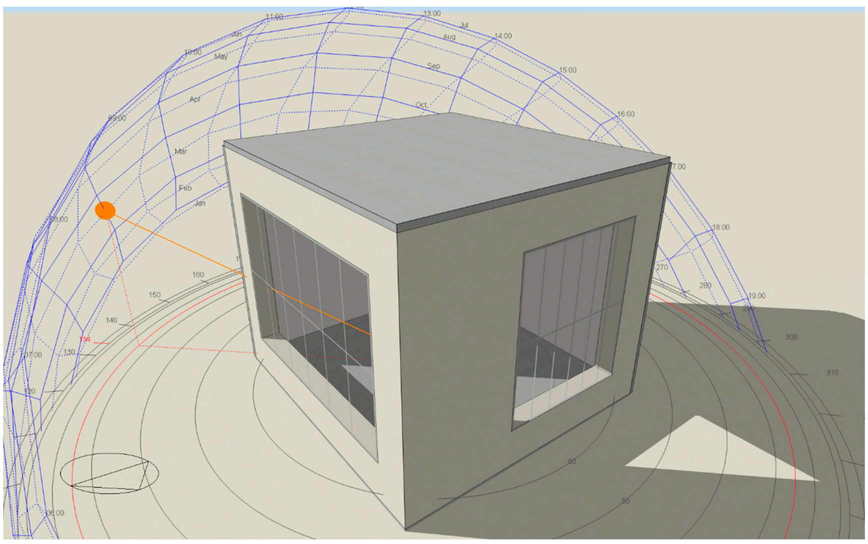

Figure 2. Office model showing shadow distribution on 1 October at 9:00 a.m.

The room was equipped with energy-saving lighting with a power of 3 W/m^2/100 lx and the following fraction: radiant equal to 0.15 and visible equal to 0.84.

Standard schedules (Table 1) implemented in the software were used: heating—Office_OpenOff_Heat, cooling—Office_OpenOff_Cool, occupancy—Office_OpenOff_Occ, lighting—Office_OpenOff_Light.

Table 1. Schedules assumed in energy simulations.

Office_OpenOff_Heat	**Office_OpenOff_Cool**	**Office_OpenOff_Light**	**Office_OpenOff_Occ**
Through: 31 December, Weekdays SummerDesignDay, up to 05:00, 0.5, up to 19:00, 1, up to 24:00, 0.5, WinterDesignDay, up to 24:00, 1, Weekends, up to 24:00, 0.5, Holidays, up to 24:00, 0.5, AllOtherDays, up to 24:00, 0;	Through: 31 December, Weekdays SummerDesignDay, up to 05:00, 0, up to 19:00, 1, up to 24:00, 0, Weekends, up to 24:00, 0, Holidays, up to 24:00, 0, WinterDesignDay AllOtherDays, up to 24:00, 0;	Through: 31 December, Weekdays SummerDesignDay, up to 07:00, 0, up to 19:00, 1, up to 24:00, 0, Weekends, up to 24:00, 0, Holidays, up to 24:00, 0, WinterDesignDay AllOtherDays, up to 24:00, 0;	Through: 31 December, Weekdays SummerDesignDay, up to 07:00, 0, up to 08:00, 0.25, up to 09:00, 0.5, up to 12:00, 1, up to 14:00, 0.75, up to 17:00, 1, up to 18:00, 0.5, up to 19:00, 0.25, up to 24:00, 0, Weekends, up to 24:00, 0, Holidays, up to 24:00, 0, WinterDesignDay AllOtherDays, up to 24:00, 0;

The set temperatures for heating and cooling were 20 °C and 24 °C, respectively, and the setback temperatures were 12 °C and 28 °C, respectively.

Energy simulation calculations were performed for the entire year using the meteorological database for Bologna Borgo Panigale 161400 (IGDG) [21]. Climatic conditions have a significant impact on the economic impact of all types of modernisation projects. Therefore, two other locations were selected, both of which contain numerous historic buildings with older-style glazing systems: Seville—Sevilla 083910 (IWEC) [22] and Paris—Paris Orly 071490 (IWEC) [23]. According to the Koppen classification, Bologna, Seville, and Paris belong to the following climate zones: Cfa (humid subtropical climate—hot summers, no dry season), Csa (Mediterranean climate—hot and dry summers), and Cfb (temperate oceanic climate—warm and not hot summers, no dry season), respectively. The next four graphs compare the weather conditions in these three selected cities. As can be seen in Figure 3, Seville is characterised by the highest outside air temperature throughout the year. This value is 29.7% and 39.6% higher than the average temperature in Bologna and Paris, respectively. It should be noted that during the winter, the temperature in Paris is higher than in Bologna. Due to the influence of the maritime climate, the highest wind speeds are recorded in Paris (Figure 4). This parameter is higher by 33.3% and as much as 58.9% compared to Seville and Bologna, respectively. The most important factor to consider when analysing the impact of window films on energy efficiency is the intensity of solar radiation. Seville is characterised by significantly higher direct solar irradiance (Figure 5) on average, by 58%, compared to other locations. However, the fluctuations of diffuse radiation are similar in all three cities (Figure 6).

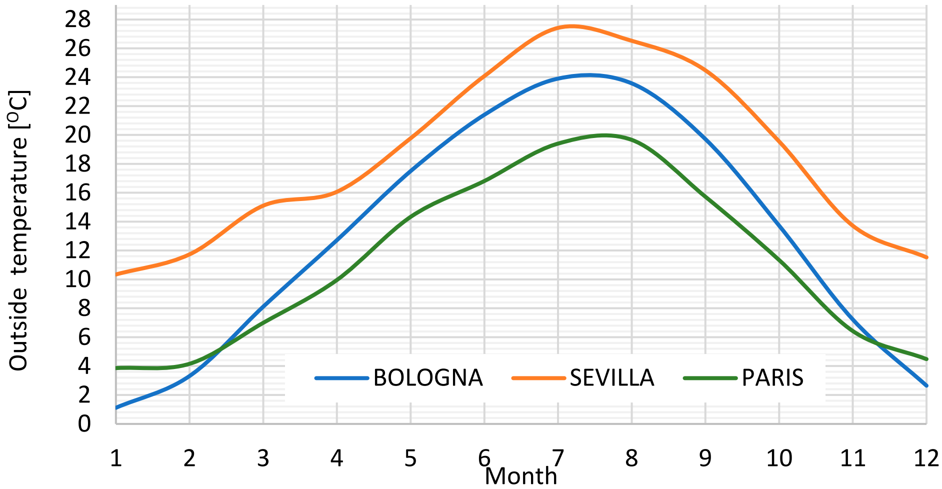

Figure 3. Outside dry-bulb temperature change during a typical meteorological year.

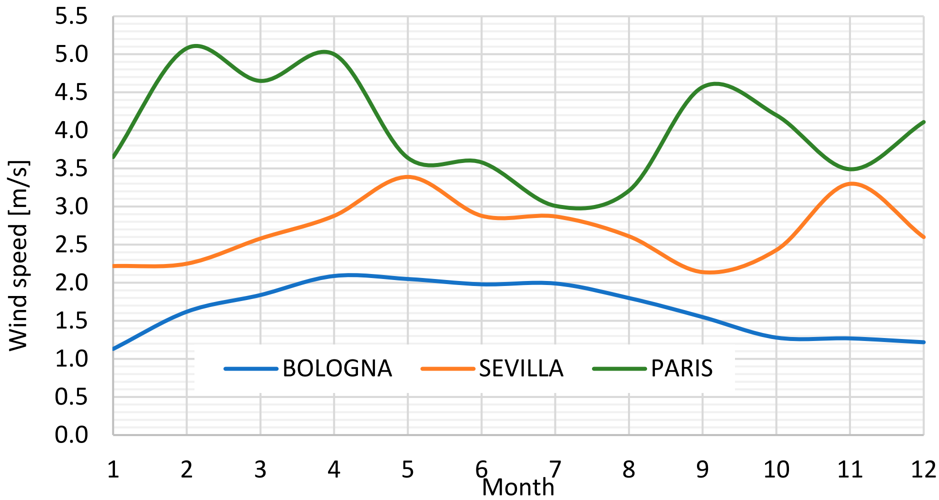

Figure 4. Average monthly wind velocity fluctuations during a typical meteorological year.

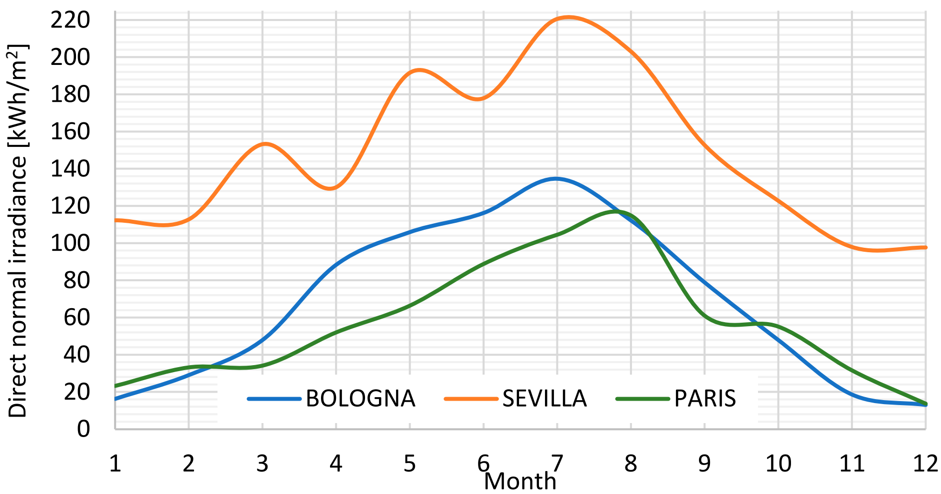

Figure 5. Average monthly direct normal solar irradiance fluctuations during a typical meteorological year.

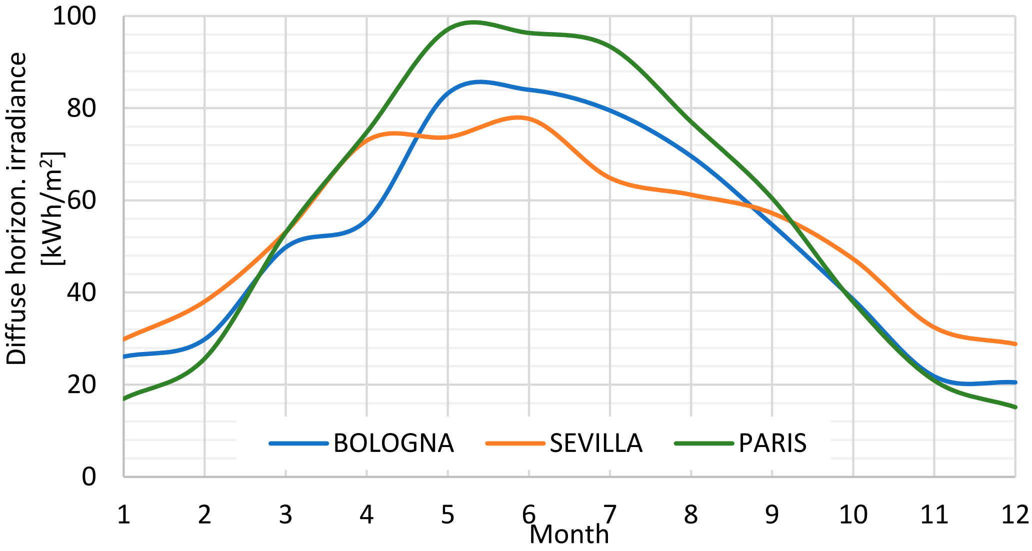

Figure 6. Average monthly diffuse horizontal solar irradiance fluctuations during a typical meteorological year.

To better describe and compare climatic conditions, it was decided to characterise them during periods that are critical from the point of view of energy consumption. Figures 7–10 show the hourly average course of ambient temperature and solar heat gains during the winter and summer design weeks. Seville has the most favourable climate conditions among the locations analysed in the winter. However, during the summer design week, Paris has by far the lowest outside temperature, while Bologna has the lowest solar heat gains. Both weather factors influence energy demand to a similar extent. It is expected that the highest energy consumption for cooling will occur in Seville.

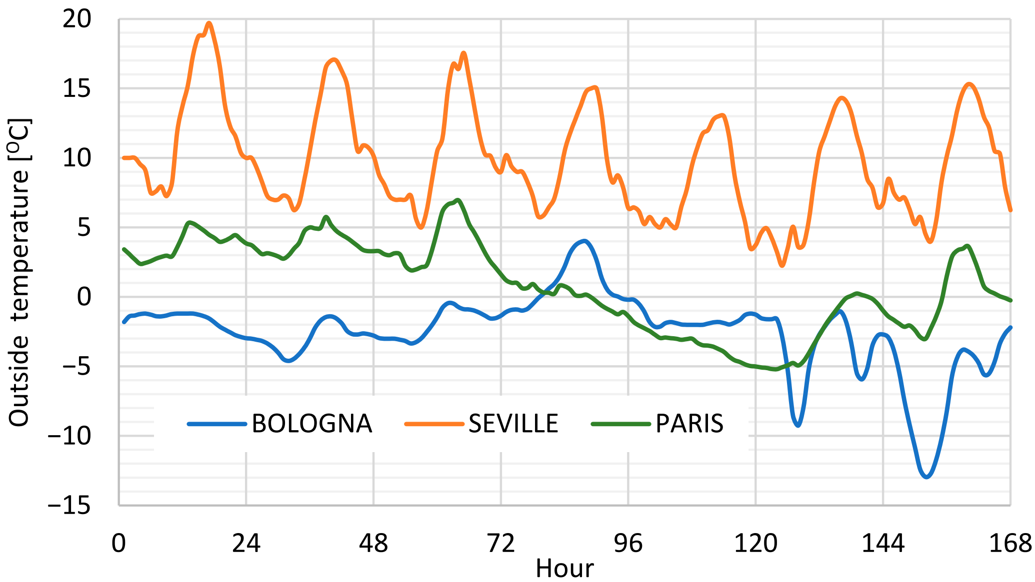

Figure 7. Average hourly change in ambient temperature during the winter design week.

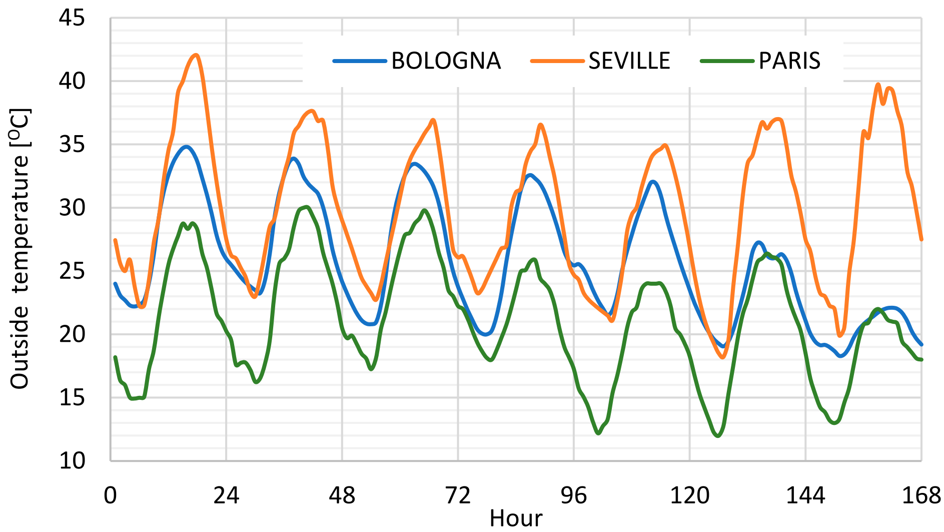

Figure 8. Average hourly change in ambient temperature during the summer design week.

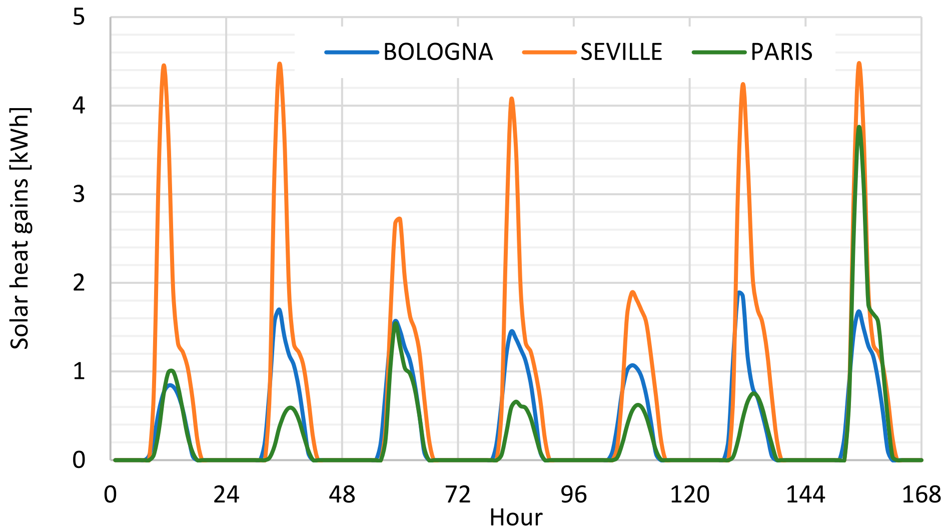

Figure 9. Average hourly change in solar heat gains during the winter design week.

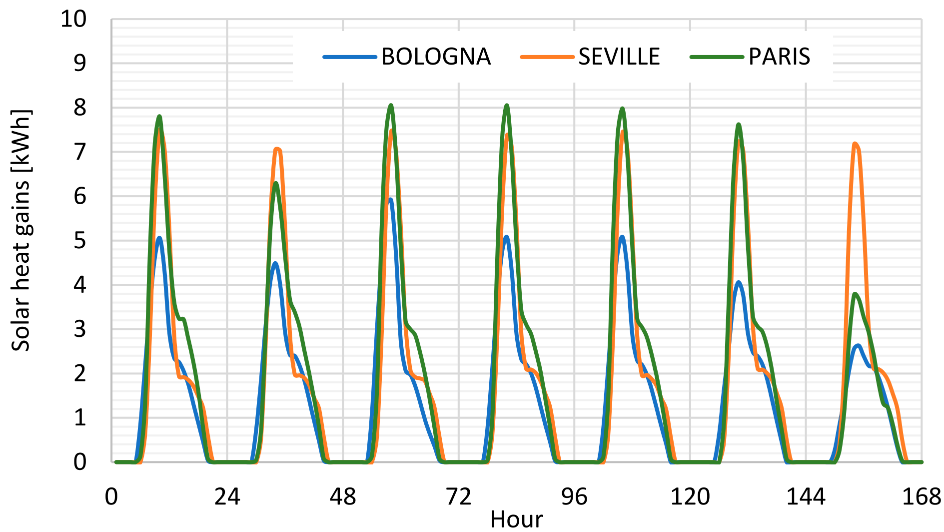

Figure 10. Average hourly change in solar heat gains during the summer design week.

2.3. Characteristics of Window Films

Berkeley Lab Optics 6.0 (Maintenance Pack 1) [24] software was used to develop glazing systems by combining sub-components. The new glazing systems consisted of 4 mm-thick clear glass with a solar control film applied to it. The calculations were based on optical, spectral, and thermal measurement data from the International Glazing Database (IGDB) version 29. Lawrence Berkeley National Laboratory, supported by the United States Department of Energy, creates and continuously develops this database.

Four foils from a renowned manufacturer marked with the following symbols: SCF_1, SCF_2 (installed externally) and SCF_3, SCF_4 (installed internally) were selected for analysis. Spectral characteristics graphs of window films determine their interaction with different wavelengths of electromagnetic solar radiation. Figure 11 shows a graph demonstrating the percentage of radiation that passes through the foil for each wavelength. The next graph (Figure 12) shows the percentage of reflected solar radiation from the front side. The percentage of radiation reflected from the back side of the foil-based glazing system is presented in the graph in Figure 13.

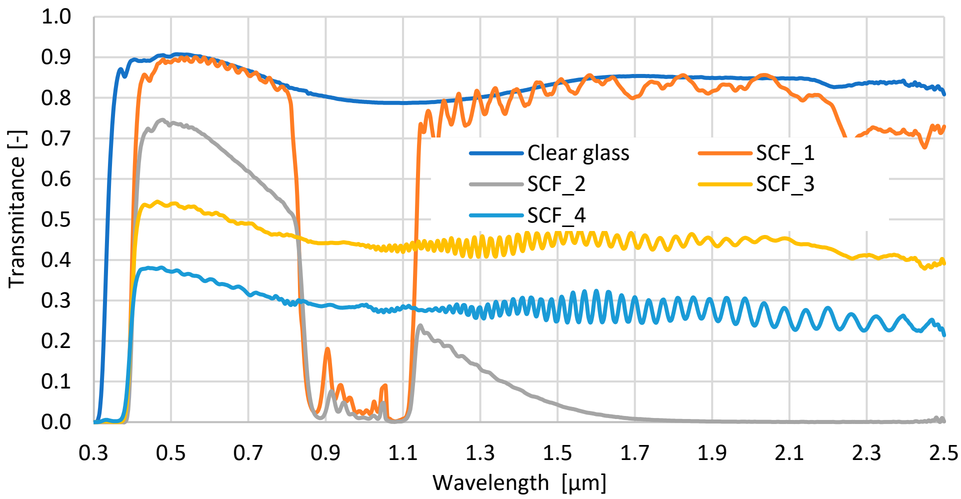

Figure 11. Spectral transmittance of the foil-based glazing system.

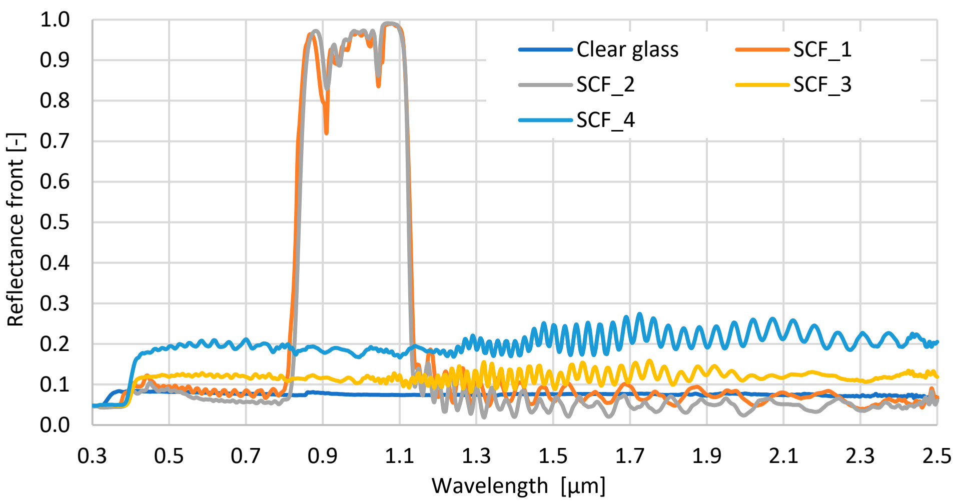

Figure 12. Spectral reflectance of the foil-based glazing system from the front side.

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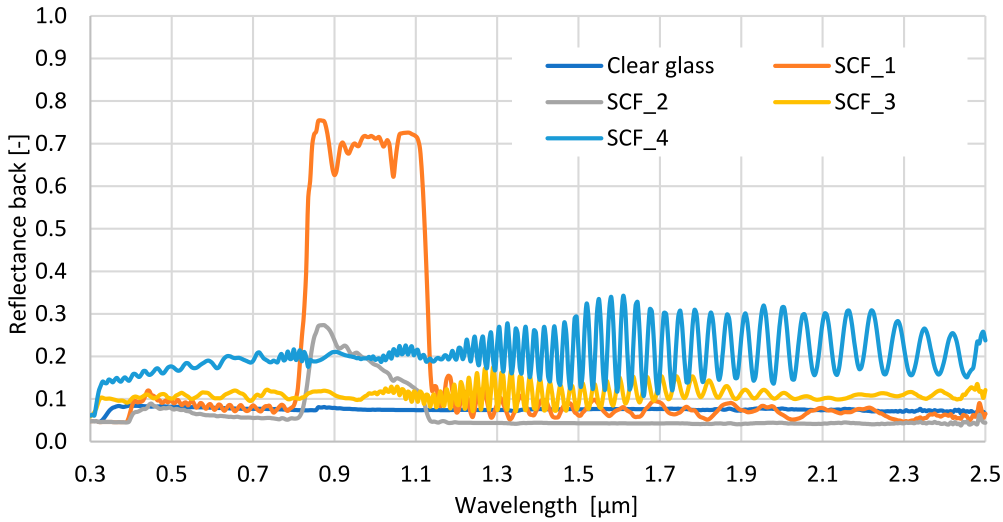

Figure 13. Spectral reflectance of the foil-based glazing system from the back side.

Solar radiation with the highest energy potential reaching the Earth's surface has wavelengths between 0.3 and 2.5 micrometres. This range includes ultraviolet radiation with wavelengths between 0.1 µm and 0.4 µm, visible light between 0.38 µm and 0.78 µm, and infrared radiation between approximately 0.78 µm and 1 µm. By integrating the above data on the graphs within the intervals corresponding to the individual radiation bands, coefficients describing their optical characteristics are determined. The optical parameters of the glass with the foil installed, which were used for the energy simulations, are presented in Table 2.

It should be noted that the spectral parameters of these SCFs may change over time. Exposure to UV radiation, high temperature and humidity can negatively affect sun protection films. Colour change, clouding resulting in reduced visible light transmission, and increased solar heat gains may result from these factors. This is particularly true for SCFs installed outside the window. In the case of photovoltaic panels, manufacturers provide the annual percentage loss of output power, known as the degradation rate. Unfortunately, there is no specific information and indicators in the scientific literature on how the properties of these films change over time. Therefore, this analysis was conducted assuming the most optimistic scenario, i.e., no change in spectral properties. In this study, SCFs from a reputable manufacturer were selected for analysis, providing a very long warranty period and operation without significant changes in optical characteristics.

Table 2. Optical characteristics of the glazing systems used in this study.

Coefficients	Clear Glass	SCF_1	SCF_2	SCF_3	SCF_4
Solar transmittance [-]	0.847	0.650	0.383	0.462	0.307
Outside solar reflectance [-]	0.078	0.264	0.245	0.118	0.188
Inside solar reflectance [-]	0.078	0.216	0.088	0.111	0.195
Visible transmittance [-]	0.902	0.892	0.718	0.562	0.361
Outside Visible reflectance [-]	0.081	0.088	0.072	0.123	0.197
Inside Visible reflectance [-]	0.081	0.087	0.068	0.108	0.179
Outside IR emissivity [-]	0.840	0.890	0.870	0.840	0.84
Inside IR emissivity [-]	0.840	0.840	0.840	0.850	0.77
Total transmission (SHGC) [-]	0.868	0.674	0.492	0.587	0.452
Light transmission [-]	0.902	0.893	0.718	0.528	0.362

2.4. Assumptions Related to Room Ventilation

The Air Changes per Hour (ACH) coefficient directly and linearly affects energy consumption during the heating season. Cold outdoor air requires sufficient heat to maintain the set internal temperature. An increase in the ACH value proportionally affects the increase in the overall heat loss coefficient (Equation (5)). In summer, excessive infiltration is also a negative phenomenon. Warm and humid outside air requires additional energy to cool it and possibly dehumidify it. Figure 14 shows the change in the average daily value of ACH over the year, which was used in the estimation of the building's energy consumption. Since the installation of solar filters does not affect the infiltration phenomenon, this issue was not analysed in detail.

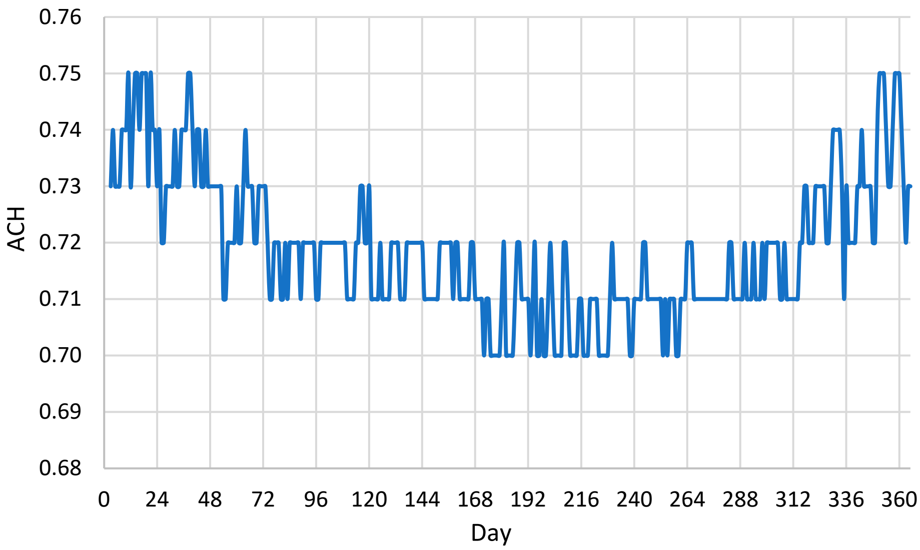

Figure 14. Air Changes per Hour over the year.

2.5. Basic Indicators Used in Financial Analysis

Three basic economic indicators: LCC, NPV, and IRR were used to examine the total installation costs of various types of window films. Based on the ISO 15686-5 standard [25], the initial costs associated with purchasing and installing window films, as well as operating costs, removal, and disposal, were determined. Maintenance costs have been omitted because the windows with foil and the windows without foil are cleaned with the same means. It was assumed that the costs of removing and disposing of the window films would require hiring a company specialising in this type of work. This would prevent potential damage to the glazed surface. Furthermore, the cost of removing SCFs installed on the interior side was reduced by 30% compared to external installation.

The current study included films manufactured by a renowned, market-leading company. These SCFs are covered by a 15-year warranty for interior installations and a 10-year warranty for exterior installations. However, the same lifetime was assumed for both types of SCFs to make this comparison objective.

Additionally, an alternative variant, BLIND, was considered to make this analysis more realistic. It was assumed that the shading element in the room would be roller blinds, which would enable cooperation with the smart home system. The price of motorised blinds, including installation, ranges from 120 EUR/m2 to 280 EUR/m2. Economic calculations assumed an initial cost of 200 EUR/m2 and a maintenance cost of 10 EUR/m2 every 5 years.

The LCC values were estimated from the following equation:

$$LCC = IC + \sum_{i=1}^{i=T} OC(i) \cdot \frac{1}{(1 + r/100)^i} + DC \cdot \frac{1}{(1 + r/100)^T} \quad (1)$$

where:

IC—construction/initial costs [EUR/m^2],
OC—annual operational costs [EUR/m^2],
DC—disposal cost [EUR/m^2]
T—life cycle period [year],
r—discount rate [%].

A summary of all costs included in the LCC analysis is provided in Table 3.

Table 3. Cost components in individual variants.

Cost Component	SCF_1	SCF_2	SCF_3	SCF_4	BLIND
Initial costs [EUR]	760.5	970.0	786.1	634.3	3708.0
Initial costs [EUR/m^2]	41.0	52.3	42.4	34.21	200.00
Operational costs [EUR]	0.00	0.00	0.00	0.00	185.40
Operational costs [EUR/m^2]	0.00	0.00	0.00	0.00	10.00
Disposal cost [EUR]	523.48	523.48	366.44	366.44	185.40
Disposal cost [EUR/m^2]	28.24	28.24	19.76	19.76	10.00

The discount rate depends on many economic factors. Current financial analyses assume that *r* ranges from 2% to a maximum of 10%. No specific value was chosen in this study, and calculations were made over the entire range of variation for this parameter.

It is impossible to establish a universal average electricity price for nearby institutions in the EU. Customers' electricity bills vary significantly, as they depend on the country (the highest costs in Germany and the lowest in Hungary) and the institution's individual contracts with the local electricity supplier. Therefore, this economic analysis assumes a price of 35 EUR per 100 kWh. As is common knowledge, energy prices are constantly rising, sometimes steadily and sometimes in bursts. Therefore, a steady increase of 2% per year in electricity prices was assumed.

Assessing the feasibility of a specific investment project is best described by the NPV. The goal should be to achieve a positive NPV after the project's life cycle. The discounted cash flows are defined by the following equation:

$$NPV = -IC + \sum_{i=1}^{i=T} \Delta CF(i) \cdot \frac{1}{(1 + r/100)^i} \quad (2)$$

where ΔCF—cash flow is the reduction in energy costs for individual variants compared to the existing operating conditions [EUR/m^2].

The actual rate of return on an investment is determined based on the IRR for a given project implementation period. In this case, an investment can be considered profitable when the IRR is greater than the cut-off discount rate r_{lim}. The formula below allows for calculating this value using the iterative method:

$$-IC + \sum_{i=1}^{i=T} \Delta CF(i) \cdot \frac{1}{(1 + r/100)^i} = 0 \quad (3)$$

2.6. Method for Adjusting Energy Simulation Results

Typically, energy simulations of buildings are performed for the weather conditions of a typical meteorological year. This means that the results are accurate for the assumed climate parameters derived from the software's database used for the calculations. If we have the actual value of solar radiation intensity and outside air temperature, we can correct the results of the calculations of energy demand for heating and cooling purposes.

This study used meteorological data from the Photovoltaic Geographic Information System (PVGIS) developed by the European Commission's Joint Research Centre. This calculation tool is available free of charge as an online application [26]. Geographical and meteorological data are used to determine detailed information about weather conditions based on precise location. The following measurements can be obtained from 2005 to 2023:

- The average value of outside air temperature,
- *GHI*—Global Horizontal Irradiation is defined as the total solar radiation on a horizontal surface.
- *DNI*—Direct Normal Irradiation is defined as the radiation received by a plane perpendicular to the solar rays.
- *kd*—Diffuse/global ratio (DIF/GHI), where DFF is Diffuse Horizontal Irradiation.

A simplified method for adjusting energy consumption calculated based on a typical meteorological year and measurement results from the PVGIS database has been proposed.

Seasonal heating energy consumption E_H can be determined using the Heating Degree Days (*HDD*) method:

$$E_H = \frac{Q_D \cdot HDD \cdot 24 \cdot \eta_H}{T_{in,D} - T_{out,D}} \tag{4}$$

where:

Q_D—design heating demand [kW]
HDD—Heating Degree Days [°C × days],
η_H—average seasonal efficiency of the heating system [-],
$T_{in,\mathrm{D}}$—indoor design temperature [°C],
$T_{out,D}$—outdoor design temperature [°C].

The relationship describing the design heat losses of the heated space Q_D can be expressed as follows:

$$Q_D = UA_T(T_{in,D} - T_{out,D}) \tag{5}$$

where UA_T—overall heat loss coefficient [kW/°C],

After inserting the above relation instead of Q_D into Equation (1) we obtain:

$$E_H = UA_T \cdot HDD \cdot 24 \cdot \eta_H \tag{6}$$

The overall heat loss coefficient, which is the sum of the coefficients responsible for heat loss through transmission (*HT*) and ventilation heat loss coefficient (*HV*), is a constant value. This means that heat losses depend directly on the air temperature difference. Also, the efficiency of a heating system does not change when comparing energy consumption in different weather conditions. Therefore, the only factor to consider is the *HDD*. Consequently, the following equation can be formulated:

$$E_{H,M} = E_{H,TMY} \times \frac{HDD_M}{HDD_{TMY}} \tag{7}$$

or

$$E_{H,M} = E_{H,TMY} \times k_H \tag{8}$$

where:

M-index denotes the value determined based on measurements,

$$k_H = \frac{HDD_M}{HDD_{TMY}}$$

In the HDD method, a base outdoor air temperature $T_{out,B}$ should be determined at which the heating should be turned on. $T_{out,B}$ equal to 15.5 °C was assumed due to the fact that the analysed object is a historic building. The *HDD* is obtained for each day of the heating period as the maximum value determined from the relationship Equation (9):

$$HDD_D = max(0, T_{out,B} - T_{out,A}) \quad (9)$$

where $T_{out,A}$ is the average daily outdoor temperature.

HDD for the entire heating season is calculated as the sum of daily values:

$$HDD_T = \sum_{i=1}^{i=n} HDD_{D,i} \quad (10)$$

where n is the number of days the heating system operates.

The Cooling Degree Days (CDD) method, analogous to *HDD*, was not used to correct cooling energy demand. The reason for not applying it was that only the outside temperature, and not the intensity of solar radiation, is taken into account in this model.

The energy balance of heat gains and losses determines the energy demand for cooling E_C. In most cases, the largest component is solar gains during the summer. The formula for calculating instantaneous heat gains Q_S from solar radiation through the window can be written as follows:

$$Q_S = I_{T,H} \cdot A \cdot SHGC \cdot F \quad (11)$$

where:

$I_{T,H}$—the intensity of total solar radiation falling on a given surface [W/m^2],
A—area of the transparent partition [m^2],
F—heat gain reduction factor for sunshades [-].

A, *SHGC*, and *F* are constant coefficients when comparing energy for cooling calculated from energy simulations and measured results. Consequently, we can assume that the EC is proportional to the intensity of total solar radiation.

Solar radiation intensity on a horizontal surface is provided in meteorological databases. However, parameters converted to vertical surfaces are used to calculate solar heat gains. In the case of direct irradiation, a conversion factor is a function of the sun's angle, which varies throughout the day and year.

Unfortunately, the analogous relationship for diffuse solar radiation intensity is more complicated. One way to simplify the description of this phenomenon is to treat this component of radiation as isotropic. This model uses the sky view factor F_{sky}. For a vertical surface, it can be assumed with high accuracy that F_{sky} = 0.5. Therefore, the intensity of total solar radiation falling on a vertical plane of the window is equal to:

$$I_{T,H} = DNI \cdot \frac{cos(\theta_V)}{cos(Z)} + 0.5DIF \quad (12)$$

This relationship is quite complex due to the change in the angle of incidence of solar radiation and the variability of the proportions between direct and diffuse radiation. Unfortunately, an accurate comparison of the $I_{T,H}$ value, derived from measurements and calculated from data from a TMY, would require writing a computer program. However, we can assume that the *GHI* value can be used for such a comparison, provided that the ratio of diffuse to global irradiation *kd* is similar in both cases.

Measurements showed that the *kd* values were equal to 0.42, 0.31, and 0.52 for Bologna, Seville, and Paris, respectively. The same coefficients calculated from computer simulations were 0.43, 0.27, and 0.50. Therefore, it can be stated that the share of diffuse radiation resulting from the level of cloud cover, atmospheric pollution and water vapour content is very similar in both cases. Since the $I_{T,H}$ is equivalent to *GHI* incident on a vertical surface,

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it can be assumed that for the purpose of estimating the energy for cooling, the following relationship can be formulated:

$$E_{C,M} = E_{C,TMY} \times \frac{GHI_M}{GHI_{TMY}} \quad (13)$$

or

$$E_{C,M} = E_{C,TMY} \times k_C \quad (14)$$

where:

$$k_C = \frac{GHI_M}{GHI_{TMY}}$$

It should be emphasised that the proposed weather correction coefficients k_H and k_C assume linear scalability. This is an accurate approach when using these indicators to model buildings with similar characteristics to the case study. There may be a decrease in accuracy in the case of different parameters related to, for example, activity schedules, shading, or heating and air conditioning systems.

3. Results and Discussion

Typically, many factors determine the optimal choice of a specific technical solution. In this case, the reduction in annual energy demand was assumed to be the decisive parameter.

3.1. Energy Simulation Results

Energy simulations were performed over the entire typical meteorological year at one-hour intervals. The results of these calculations, including energy consumption for artificial lighting, cooling, and heating, are summarised in Table 4.

Table 4. Energy consumption divided into three basic components.

Components of Energy Demand [kWh]	Clear Glass	SCF_1	SCF_2	SCF_3	SCF_4	BLIND
Interior Lighting	177.29	177.58	181.67	190.48	204.86	177.41
Heating	3653.77	3925.69	4059.81	3883.96	3973.16	3820.76
Cooling	2341.85	1806.96	1510.05	1800.78	1526.06	1610.6
Total energy consumption	6172.91	5910.23	5751.53	5875.22	5704.08	5608.77

The level of natural lighting in occupied spaces depends on the amount of visible solar radiation passing through the glazing system. The higher the coefficient of Visible Transmittance (VT), the more natural light passes into the room. Of course, this translates into reduced electricity bills. As can be seen from the analysis of the results in Table 3, the use of window film reduces the amount of natural light. In this regard, SCF_4 exhibits the worst performance, increasing electricity consumption for lighting by approximately 15.5%.

SCF_2 window film has the lowest SHGC value. Thanks to this optical characteristic, energy demand for cooling is reduced by 35.5% compared to the initial variant, i.e., a single-pane window without shading elements. Unfortunately, the low transmission of solar energy into the office interior resulted in the largest increase (11.1%) in energy consumption for heating compared to other cases. Roller blinds proved to be a slightly better shading option compared to SCFs. After accounting for all energy consumption components, a 9.1% reduction in electricity demand was achieved. Among window filters, SCF_4 proved to be the most effective, reducing total energy consumption by 7.6%.

Table 5 presents the percentage differences between the energy demand in the other two locations compared to the baseline value for Bologna. A negative value indicates that individual components of the energy balance have a higher value for Bologna. The calculation results presented in Table 4 clearly show that the highest total energy demand occurs in the office located in Bologna, being 11.5% and 20.7% higher compared to the locations in Paris and Seville, respectively.

Table 5. Energy demand compared to Bologna.

Components of Energy Demand [%]	Clear Glass	SCF_1	SCF_2	SCF_3	SCF_4	BLIND
				Seville		
Interior Lighting	−4.17	−4.19	−4.60	−5.92	−8.15	−4.07
Heating	−84.13	−80.60	−77.80	−80.07	−77.77	−79.32
Cooling	77.02	79.60	79.83	77.81	79.16	75.26
Total energy consumption	−20.70	−29.32	−34.10	−29.28	−33.28	−32.55
				Paris		
Interior Lighting	10.02	10.07	10.45	10.43	10.05	10.04
Heating	2.88	4.08	6.98	6.40	7.49	5.84
Cooling	−35.59	−44.97	−53.71	−47.76	−53.84	−47.12
Total energy consumption	−11.51	−10.73	−8.84	−10.07	−8.83	−9.24

Tables 4 and 5 contain final energy values, i.e., useful energy plus losses incurred during its conversion and transmission.

Reduction in energy consumption resulting from the use of individual shading elements cannot be the only factor influencing the recommended solution. Therefore, a financial analysis should be performed to guide this type of decision.

3.2. Cost Analysis Results

The simulation results were used to determine the total annual energy costs and the differences in these costs for the individual cases analysed in this study. The remaining indicators used in the calculations are described and presented in Section 2.5.

An objective assessment of the costs of window shading systems throughout their entire life cycle, i.e., from installation to disposal, can be made based on life cycle costing. The graph presented in Figure 15 allows for making an effective economic decision that accounts for the total investment costs and the variability of the discount rate.

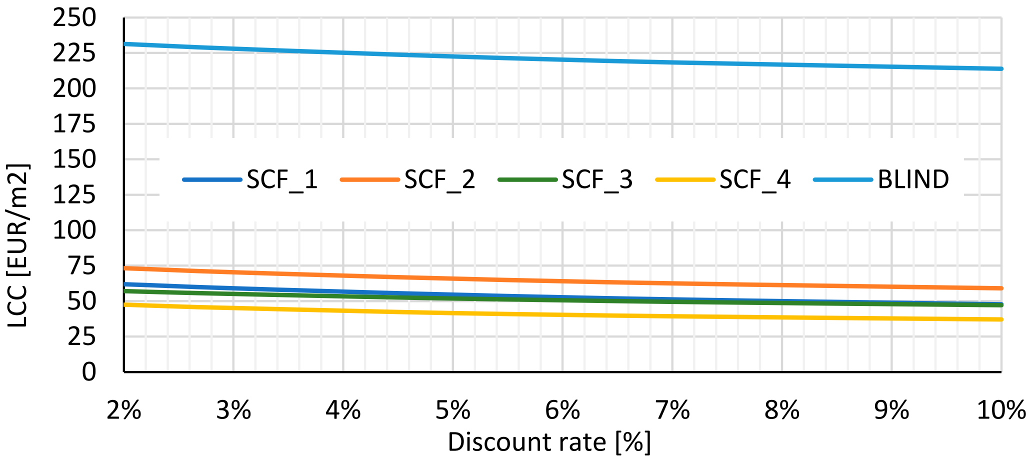

Figure 15. LCC value as a function of the discount rate for all cases analysed.

Figure 15 clearly shows that the lowest life cycle cost is achieved by the SCF_4 film installed from the inside. It should also be noted that in the energy analysis, this shading element was also demonstrated to be the most efficient among window films. Unfortunately, roller blinds were by far the most capital-intensive solution due to the very high initial costs.

The most useful tool for assessing the cost-effectiveness of a project from a financial perspective is the NPV indicator. In determining the NPV, it was assumed that the cash flows represented the reduction in energy consumption resulting from the installation of shading elements. The NPV should not be negative to obtain a satisfactory financial result in the desired time perspective. For all window foils, the NPV was positive and amounted to 30.36 EUR/m^2 for SCF_1, 70.85 EUR/m^2 for SCF_2, 44.93 EUR/m^2 for SCF_3, and 108.4 EUR/m^2 for SCF_4. Installing roller blinds will not be economically justified, as the NPV was equal to −47.68 EUR/m^2.

The use of SCFs certainly does not involve significant financial risk. A discount rate of 5% to 10% maximum is assumed for such projects. The trend in IRR changes over time for Bologna is visible in Figure 16. It turns out that the use of SCF_4 window film can achieve a 10% discount rate after just 5 years. In the case of roller shutters, the discount rate will approach 0% only at the end of the life cycle.

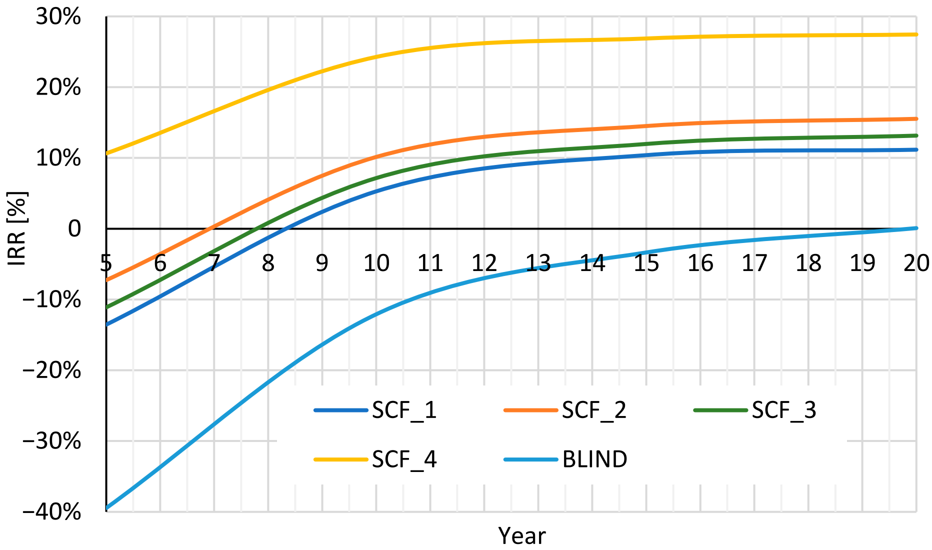

Figure 16. IRR value as a function of investment evaluation time for Bologna.

The use of shading elements in other locations is characterised by similar trends in economic indicators in relation to Bologna. As one might expect, the greatest financial benefits can be obtained in areas with high levels of sunlight, such as Seville. The NPV is 178.37, 292.86, 188.64, 310.18, and 130.27 EUR/m2 for SCF_1, SCF_2, SCF_3, SCF_4, and BLIND, respectively. The economic effect is definitely worse in the case of locating this type of investment in Paris. The NPV turns out to be several times lower and is: 5.58, 5.45, 6.38, and 41.35 EUR/m2 for SCF_1, SCF_2, SCF_3, and SCF_4, respectively. Installing roller shutters in the climatic conditions of Paris is economically unjustified, as is the case in Bologna, because the NPV is negative and equal to −110.16 EUR/m^2.

The IRRs for Seville (Figure 17) demonstrate that installing SCFs will be an excellent investment. The rate of return will exceed 20% after just 5 years for all cases subject to this analysis. However, in the weather conditions of Paris (Figure 18), the discount rate will increase above 10% only after more than 10 years for the SCF_4 foil. Installing roller shutters turns out to be the least profitable investment, as the IRR will reach 5% only after 10 years and will not exceed 10% after 20 years. In maritime climates (Paris), the discount rate will be negative throughout the entire life cycle.

The analysis of financial indicators points towards the primary conclusion that the SCF_4 window film is the most cost-effective solution for the three climatic conditions considered in this case study.

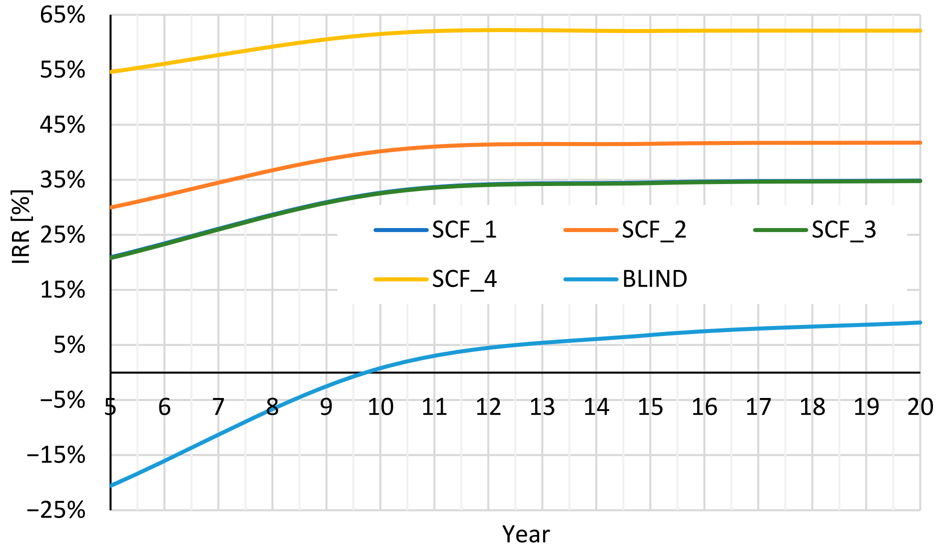

Figure 17. IRR value as a function of investment evaluation time for Seville.

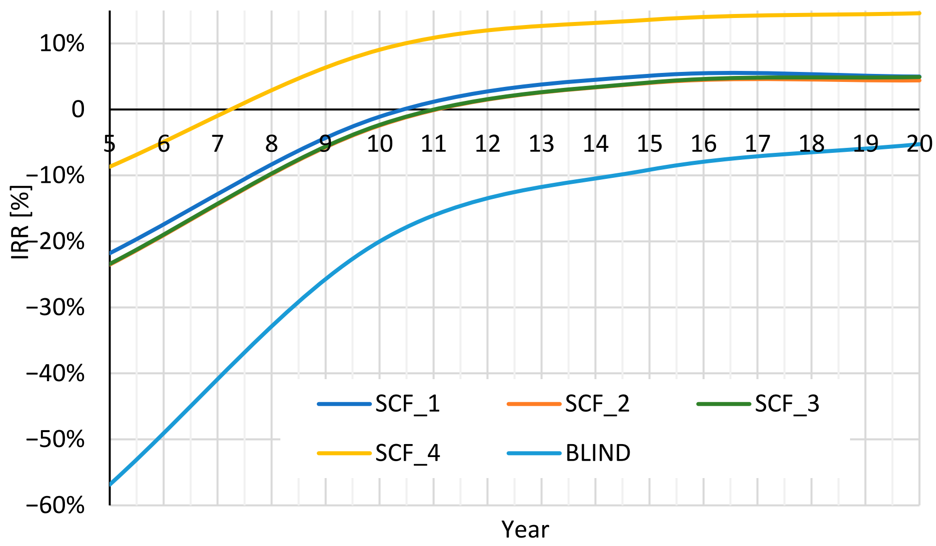

Figure 18. IRR value as a function of investment evaluation time for Paris.

3.3. Energy Consumption Correction Factors

To correct the energy consumption under meteorological conditions derived from measurements [26], the coefficients kH and kC in Equations (8) and (14) were determined. For heating energy demand, the k_H values are 0.89, 0.93, 0.99 for Bologna, Seville and Paris, respectively. This means that the $E_{H,M}$ value will be lower after accounting for the average climatic conditions in 2005–2023. Considering the correction for cooling energy consumption, the k_C values are equal to 1.04, 0.79, and 0.90 for Bologna, Seville, and Paris, respectively. Therefore, the $E_{C,M}$ value will increase in Bologna, while in the other two locations it will decrease. The coefficient values given above can be used to correct the results of energy simulations based on meteorological data for TMY conditions.

3.4. Solar Heat Gains Depending on Window Orientation

The above analysis was performed for a specific case of building orientation. To generalise this study, solar gains were calculated depending on window orientation. The results for the clear glass glazing in individual months are presented in Table 6.

Table 6. Solar gains $Q_{S,CG}$ in kWh for a clear 1 m^2 window pane depending on its orientation.

Month	1	2	3	4	5	6	7	8	9	10	11	12
						Bologna						
North	9.41	11.25	18.78	22.73	33.13	34.94	34.20	28.59	21.73	15.02	8.15	7.40
East	12.75	16.99	29.61	42.74	57.73	60.45	63.58	53.98	39.30	24.36	11.29	9.90
South	25.79	33.80	46.93	56.71	57.37	52.20	57.76	61.84	60.88	48.53	24.01	20.98
West	12.62	17.06	29.89	42.67	57.78	60.53	63.74	54.33	39.42	24.63	11.37	9.86
						Seville						
North	14.13	17.27	24.73	29.83	35.49	37.12	35.76	31.07	26.11	21.08	14.76	13.24
East	31.75	39.15	57.11	61.72	77.53	72.36	79.39	72.89	58.23	45.70	30.58	28.58
South	88.34	82.15	87.89	65.47	54.10	46.07	50.92	66.52	81.39	87.10	79.36	82.89
West	34.58	39.89	56.23	60.40	78.71	75.66	82.32	75.45	58.20	44.62	31.51	28.91
						Paris						
North	7.06	12.64	23.88	34.22	44.84	47.80	48.15	41.39	29.02	19.24	10.29	6.87
East	10.35	17.88	31.17	47.75	65.56	70.01	74.50	70.43	43.26	30.62	15.53	8.57
South	26.22	37.87	48.62	61.27	63.90	64.81	70.39	77.15	62.59	56.09	35.18	20.12
West	10.65	18.68	32.06	47.08	61.45	71.21	74.95	70.43	45.64	30.30	15.78	8.93

To estimate the heat gain for a solar filter with a given *SHGC* value, the following formula can be used:

$$Q_{S,SCF} = Q_{S,CG} \times \frac{SHGC}{0.868} \tag{15}$$

3.5. The Impact of SCFs on Thermal Comfort

To assess the impact of window films on thermal comfort, the operative temperature (the average of the mean radiant and air temperatures) was determined for the base case and after applying SCF_4. As shown in Figure 19, the solar filter did not negatively affect thermal conditions due to the low level of solar radiation during the winter design week. During periods of high solar heat gains, we can notice a significant reduction in the operative temperature in the room, reaching up to 3.5 °C in the first days of the designed summer week.

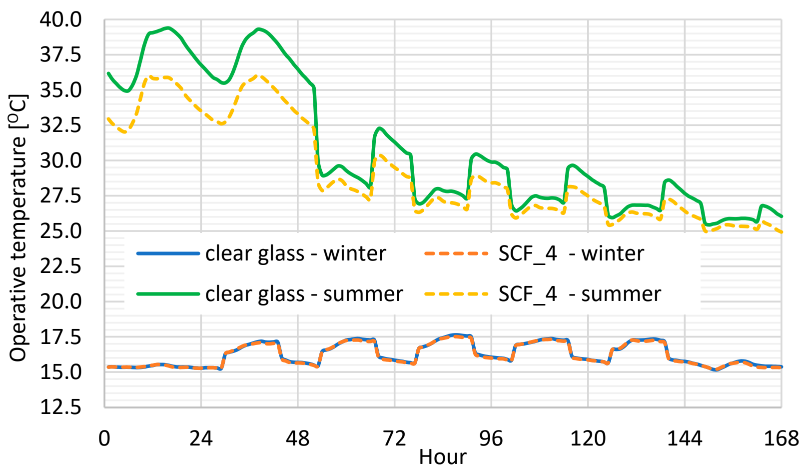

Figure 19. Summer and winter design week indoor operative temperature.

3.6. The Influence of Thermal Inertia on Energy Consumption

The thermal capacity of a building structure influences energy consumption and thermal comfort (Li et al. [27]). Historical buildings are typically characterised by massive construction. Therefore, the Internal Thermal Mass option was used in the model to determine the impact of thermal capacity on energy demand. Three sets of calculations were performed for the baseline variant, i.e., the clear glass and the SCF_4 filter. The mass of the inter-story ceiling was changed by 100% in each variant. For the baseline variant, increasing internal thermal capacity by 100% and 200% led to a reduction in energy consumption by 1% and 1.8%, respectively. Installing SCF_4 resulted in a smaller impact of 0.8% and 1.6%, respectively. These results are not significant, but the phenomenon analysed here would require a more extensive analysis in the context of night-time cooling using outdoor air. Unfortunately, the historic building used as the case study does not have openable windows, so this option was not studied.

4. Summary and Conclusions

Solar control films installed on glazing are an effective modernisation solution that improves the energy efficiency of historic buildings. Very often, the absence of interference with the facades is a key requirement of the conservator when approving investment projects. Windows replacement is usually impossible, but window film can be applied to existing, often single-glazed, windows.

The most important achievements of this research are listed below.

1. The application of SCFs significantly reduces cooling energy demand in warmer months. Moreover, limiting heat gains from solar radiation decreases the internal air temperature, resulting in improved thermal comfort. The window filters examined in this study can reduce the energy consumption for air cooling by 22.8% (SCF_1) to 35.5% (SCF_2) in the case of Bologna. In the case of Mediterranean climate conditions, i.e., Seville, these values are similar and range from 21.7% (SCF_1) to 34.5% (SCF_2). It turned out that the highest reduction, ranging from 34.1% (SCF_1) to 53.7% (SCF_2), can be achieved in the case of an office location in Paris. The share of cooling energy in the total balance is about 27.6% in temperate oceanic climate conditions.
2. On the other hand, the reduction in the amount of solar energy entering rooms leads to an increase in energy demand for heating during winter. These values contribute to the total energy balance to a greater or lesser extent and are within the following ranges: from 6.3% (SCF_2) to 11.1% (SCF_3) in the case of Bologna, from 31.4% (SCF_2) to 55.4% (SCF_3) in the case of Seville, and from 8.7% (SCF_2) to 15.5% (SCF_3) for the location in Paris. It should be noted that in Mediterranean climate conditions, the percentage increases in energy demand for heating are very high. However, on the other hand, the share of heating in the total energy balance is only 12%.
3. Typically, window foils also reduce the amount of visible light entering occupied rooms. This consequence leads to extending the operation of artificial lighting. However, the increase in energy consumption for lighting is small, ranging from 0.2% (SCF_1) to 15.6% (SCF_4) in the case of Bologna and Paris, and from 0.1% (SCF_1) to 10.8% (SCF_4) in the case of Seville. Additionally, the share of electricity for lighting is slight, ranging from 2.9% for Bologna to 3.6% for Paris, in the total energy demand.
4. A simple method for correcting the results of energy simulations of buildings using implemented weather data has been proposed. These debases reflect the characteristics of a so-called typical meteorological year, and data collection took place at different time intervals. It is unknown whether they account for recent climate changes. Using publicly available measurements from the PVGIS portal, the correction coefficients k_H and k_C were determined. Adjusted values corresponding to weather conditions from the last 19 years can be obtained by multiplying the simulation results by k_H and k_C. The k_H values are 0.89, 0.93, 0.99 for Bologna, Seville and Paris, respectively, when converting energy consumption for heating purposes. However, when correcting the cooling energy consumption, the following k_C coefficients should be used: 1.04, 0.79 and 0.90 for Bologna, Seville and Paris, respectively.

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5. It should be emphasised that selecting the appropriate SCF is a complex issue, and a universal solution cannot be offered. First, the ratio between reflected and transmitted solar radiation must be determined. Local climatic conditions and the optical characteristics of the existing glazing are key factors influencing this parameter. The next step is a thorough economic analysis, considering discounted cash flows and potential changes in energy prices. Detailed evaluation of financial indicators such as LCC, NPV, and IRR led to the clear selection of SCF_4 foil. Installing this window film will provide the most cost-effective technical solution for all three different climatic conditions considered in this case study.

It should be noted that the selection of the optimal SCF for a given room depends on many parameters. One of them may be shading from adjacent buildings or trees with variable transparency to solar radiation throughout the year. Therefore, making the right decision should take into account not only weather parameters but also local urban conditions.

Future work: Research into new types of window films with nanostructures is currently underway by the development company with which the authors of this article are collaborating. Following the completion of the laboratory tests, it is planned to apply this film, among others, at the University of Bologna. Experimental examinations will then be conducted to determine the characteristics of the new SCF under operational conditions.

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Data Availability Statement: The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

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

Abbreviations

The following abbreviations are used in this manuscript:

ACH	Air Changes per Hour
DNI	Direct Normal Irradiation
DIF	Diffuse Horizontal Irradiation
GHI	Global Horizontal Irradiation
HDD	Heating Degree Days
IRR	Internal Rate Of Return
LCC	Life Cycle Costing
NPV	Net Present Value
PVGIS	Photovoltaic Geographical Information System
SCFs	Solar Control Foils
SHG	Solar Heat Gains
SHGC	Solar Heat Gain Coefficient
TMY	Typical Meteorological Year

References

1. National Institute of Building Sciences—NIBS. Available online: https://www.wbdg.org/resources/window-film-fundamentals (accessed on 22 December 2025).
2. Pereira, J.; Teixeira, H.; Gomes, M.d.G.; Moret Rodrigues, A. Performance of Solar Control Films on Building Glazing: A Literature Review. *Appl. Sci.* **2022**, *12*, 5923. [CrossRef]
3. Bahadori-Jahromi, A.; Rotimi, A.; Mylona, A.; Godfrey, P.; Cook, D. Impact of Window Films on the Overall Energy Consumption of Existing UK Hotel Buildings. *Sustainability* **2017**, *9*, 731. [CrossRef]
4. Wang, H.; Hang, J.; Yang, J.; Gao, Z.; Zhao, J.; Xu, F. Reduced-scale experimental study on the cooling effect of solar control films and cool materials. *Energy Build.* **2024**, *320*, 114636. [CrossRef]
5. Lu, M.; Zeng, L.; Li, Q.; Hang, J.; Hua, J.; Wang, X.; Wang, W. Quantifying cooling benefits of cool roofs and walls applied in building clusters by scaled outdoor experiments. *Sustain. Cities Soc.* **2023**, *97*, 104741. [CrossRef]
6. Xamán, J.; Olazo-Gómez, Y.; Zavala-Guillén, I.; Hernández-Pérez, I.; Aguilar, J.O.; Hinojosa, J.F. Thermal evaluation of a Room coupled with a Double Glazing Window with/without a solar control film for Mexico. *Appl. Therm. Eng.* **2017**, *110*, 805–820. [CrossRef]
7. Teixeira, H.; Gomes, M.d.G.; Moret Rodrigues, A.; Pereira, J. In-Service Thermal and Luminous Performance Monitoring of a Refurbished Building with Solar Control Films on the Glazing System. *Energies* **2021**, *14*, 1388. [CrossRef]
8. Li, D.H.; Lam, J.C.; Lau, C.C.; Huan, T.W. Lighting and energy performance of solar film coating in air-conditioned cellular offices. *Renew. Energy* **2004**, *29*, 921–937. [CrossRef]
9. Calama-González, C.M.; León-Rodríguez, Á.L.; Suárez, R. Daylighting Performance of Solar Control Films for Hospital Buildings in a Mediterranean Climate. *Energies* **2019**, *12*, 489. [CrossRef]
10. Pereira, J.O.; Gomes, M.G.; Rodrigues, A.M.; Teixeira, H.; Almeida, M. Small-scale Field Study of Window Films' Impact on Daylight Availability under Clear Sky Conditions. *J. Facade Des. Eng.* **2020**, *8*, 65–84. [CrossRef]
11. Noh-Pat, F.; Xamán, J.; Álvarez, G.; Chávez, Y.; Arce, J. Thermal analysis for a double glazing unit with and without a solar control film (SnS–CuxS) for using in hot climates. *Energy Build.* **2011**, *43*, 704–712. [CrossRef]
12. Chaiyapinunt, S.; Phueakphongsuriya, B.; Mongkornsaksit, K.; Khomporn, N. Performance rating of glass windows and glass windows with films in aspect of thermal comfort and heat transmission. *Energy Build.* **2005**, *37*, 725–738. [CrossRef]
13. Moretti, E.; Belloni, E. Evaluation of energy, thermal, and daylighting performance of solar control films for a case study in moderate climate. *Build. Environ.* **2015**, *94*, 183–195. [CrossRef]
14. Pereira, J.; Gomes, M.D.; Rodrigues, A.M.; Almeida, M. Thermal, luminous and energy performance of solar control films in single-glazed windows: Use of energy performance criteria to support decision making. *Energy Build.* **2019**, *198*, 431–443. [CrossRef]
15. Teixeira, H.; Gomes, M.G.; Rodrigues, A.M.; Pereira, J. Thermal and visual comfort, energy use and environmental performance of glazing systems with solar control films. *Build. Environ.* **2020**, *168*, 106474. [CrossRef]
16. Pereira, J.; Rivero, C.C.; Gomes, M.G.; Rodrigues, A.M.; Marrero, M. Energy, environmental and economic analysis of windows' retrofit with solar control films: A case study in Mediterranean climate. *Energy* **2021**, *233*, 121083. [CrossRef]
17. Taqi, H.H.; Maheshwari, G.P.; Alasseri, R. Cost Effectiveness for Solar Control Film for Residential Applications. In Proceedings of the 10th International Conference Enhanced Building Operations, Shuwaikh, Kuwait, 26–28 October 2010.
18. Chan, W.W.; Mak, L.M.; Chen, Y.M.; Wang, Y.H.; Xie, H.R.; Hou, G.Q.; Li, D. Energy Saving and Tourism Sustainability: Solar Control Window Film in Hotel Rooms. *J. Sustain. Tour.* **2008**, *16*, 563–574. [CrossRef]
19. Hui, S.C.M.; Kwok, M.K. Study of thin films to enhance window performance in buildings. In Proceedings of the Sichuan-Hong Kong Joint Symposium 2006, Chengdu, China, 30 June–1 July 2006.
20. The U.S. Department of Energy—EnergyPlus. Available online: https://www.energy.gov/eere/buildings/articles/energyplus (accessed on 22 December 2025).
21. EnergyPlus—Weather Data by Location. Available online: https://energyplus.net/weather-region/europe_wmo_region_6/ITA (accessed on 22 December 2025).
22. EnergyPlus—Weather Data by Location. Available online: https://energyplus.net/weather-region/europe_wmo_region_6/ESP (accessed on 22 December 2025).
23. EnergyPlus—Weather Data by Location. Available online: https://energyplus.net/weather-region/europe_wmo_region_6/FRA (accessed on 22 December 2025).
24. Lawrence Berkeley National Laboratory—Optics. Available online: https://windows.lbl.gov/software-tools#optics-heading (accessed on 22 December 2025).
25. *ISO 15686-5:2017*; Buildings and Constructed Assets—Service Life Planning, Part 5: Life-Cycle Costing. ISO: Geneva, Switzerland, 2017.

26. PVGIS: Photovoltaic Geographical Information System. Available online: https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html (accessed on 22 December 2025).
27. Li, Y.; Wang, C.; Li, G.; Wang, J.; Zhao, D.; Chen, C. Improving operational flexibility of integrated energy system with uncertain renewable generations considering thermal inertia of buildings. *Energy Convers. Manag.* **2020**, *207*, 112526. [CrossRef]