Solar Control Films for Building Glazings

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Buildings with a high window-to-wall ratio tend to suffer from excessive solar gains/losses that usually result in high energy demand and discomfort for occupants. Solar control films (SCFs) are a passive solution with the potential to increase the performance of new or refurbished glazing they are applied to. The presence of SCFs can significantly reduce indoor solar radiation and illuminance levels, particularly with reflective films applied to south-oriented glazing (north hemisphere). Glazing systems with SCFs were reported to promote cooling energy savings compared with clear glazing in hot climates. Studies have explored the visual and thermal comfort performance of SCFs, concluding that these films promote thermal comfort, and reduce excessive illuminance and potential glare.

solar control film | thermal performance | luminous performance | energy performance | indoor comfort

1. Introduction

The increasing world population and the improvement of people's living conditions have caused a significant increase in global energy needs. The worldwide energy consumption by the building sector has increased and currently accounts for 40% of the world's energy consumption and for approximately 36% of the greenhouse gas emissions [1][2][3], making it a key sector in national economies with a strong potential in energy saving and emission reduction. The topic of energy efficiency in buildings has been the center of a broad technical and scientific discussion in recent years concerning the decarbonization or carbon neutrality of the building sector. In that sense, several innovative materials for opaque and transparent [4] elements of building envelopes, high-performant lighting systems, and more efficient heating and cooling systems that maximize energy savings have been investigated and developed in the last decades. When compared with opaque elements, glazed elements of a building envelope usually have a lower performance due to their higher thermal and solar transmittance. However, glazed elements can positively impact the luminous quality of the indoor environment since they provide occupants with an outdoor view and make it possible to benefit from daylight. Therefore, glazing systems are one of the most significant elements concerning the thermal and visual comfort, and energy efficiency in buildings [5][6][7].

Since modern buildings tend to have large glazing areas, and conventional glazing leads to significant heat exchanges between the indoor and outdoor environments and high indoor illuminance levels that can cause discomfort glare, it is important to promote solar control solutions that can enhance the performance of windows. Some of these more conventional solutions, such as overhangs, blinds and louvers, have, as drawbacks, the requirement of altering the type or structure of the existing glazing/fenestration and the possible blocking of the outdoor view.

Research and development in the field of glazing systems have experienced a rapid evolution with several innovative breakthroughs, such as laminated glass panes in the 1920s and coated products in the 1970s. Since then, the traditional clear single-glass window, which has a poor performance, has evolved to produce more efficient solutions such as double or triple glazing, low-emittance windows with low thermal transmittance, vacuum glazing, electrochromic windows [8][9], thermotropic materials [10][11], silica aerogels [12] and transparent insulation materials. More recently, the development of transparent selective coatings and films [13][14][15] provides a wide range of solar optical properties for glazing surfaces, admitting high daylight levels while preventing excessive heat gains through the glazing.

Some of these innovative and modern window technologies [8][10][11] can dynamically alter their properties to control the amount of incoming light and heat by responding to environmental stimuli or user requirements. As a result, these smart window technologies can improve the building’s global performance by optimizing energy use, peak demand and indoor comfort in real time. Smart window technologies have undergone rapid development in the last years, particularly in windows that respond to electro-, thermos-, mechano- and photo- stimuli [4]. Electrochromic windows are a promising and attractive window technology from research, design and user perspectives, with several products currently available in the market. This type of smart window has a better performance in climates with different needs for winter and summer seasons and different façade orientations [9][16]. Photochromic and thermotropic passive smart windows that react to light and heat stimuli, respectively, are also attractive solutions with a lower economic cost than active windows [10][11][17]. Nevertheless, these passive smart windows have as drawback the impossibility for users to control their switching state.

The main issues involved in the application of smart windows are: the high cost and associated long payback period; the materials and devices must be highly durable; the optimization of the solar modulation properties to achieve maximum energy savings; the potential presence of the haze effect, usually caused by disperse particle technology.

The installation of static solar control films (SCFs) is an alternative and effective solution to reduce heat gains through glazing systems by altering their solar optical and thermal properties. With an easy application method that does not require façade alteration, these films act as refurbishment solutions that promote the improvement of the thermal, luminous and energy performance of building glazing, while reducing potential glare and the transmittance of ultraviolet (UV) radiation. Furthermore, these static films present a lower economic cost than the dynamic window technologies previously mentioned.

2. Solar Control Films

A solar control film (SCF), as previously referred to, is a thin laminate film that is applied to glazing systems to modify their solar optical and thermal properties in order to increase their performance. Currently, there is a broad variety of SCFs for new and retrofitted glass, with application on both internal and external glass surfaces, which are suitable for cold and hot climates.

2.1. Types of Solar Control Films

The main industry players of window films (such as 3M [18]; Llumar [19]; Avery Dennison [20]; Solar Gard [21]; and Johnson Window Films [22]) offer a large variety of each type of SCFs to be installed in different positions of the glazing system. Depending on their purpose, SCFs can be divided into the following types:

- Reflective: these films have reflective properties on both sides that provide high heat, glare and UV control. They give a silvery/mirrored look to the glazing when viewed with indoor lighting or outdoor daylight.
- Dual-reflective: these films have a reflective outside-facing layer with a subtler inside-facing layer, meaning they can provide significant solar control during the day and maintain a clear outside view at night.
- Neutral: these films control solar gains through the glass while maintaining the original appearance of the glazing system.
- Low emissivity: these films reduce the thermal transmittance coefficient (U-value) of the glazing system, increasing its thermal insulation and heat-rejection properties during the four seasons (suitable for temperate regions).
- Spectrally selective: these films offer an excellent heat rejection with a virtually invisible appearance. Contrary to neutral SCFs, spectrally selective films can block specific regions of the solar spectrum associated with solar heat gains while not penalizing the transmittance of daylight through the glazing.
- Ceramic: these films offer solar control without a metal layer, maintaining a low visible reflectivity and a high resistance to corrosion (suitable for coastal areas).
- Safety and protection: these films can control excessive solar heat gains and, at the same time, increase the resistance of the glass pane to intentional or accidental impacts. In addition, this type of film reduces the amount and dimension of potential glass fragments and/or offers higher resistance to the glass to support shock waves from explosions and/or ballistic attacks.

Information on the thermal and solar optical properties of the SCFs available on the market was gathered in the work to better understand the range of values of each property and help to highlight the differences between the multiple types of SCFs. The properties of the SCFs stored in the International Glazing Database [23] were collected using Optics [24] and Window [25] software. The version (v72.0) of the IGDB database used for the work has, in total, 156 SCFs manufactured by some of the main industry players of window films (3M [18]; Llumar [19]; Avery Dennison [20]; Solar Gard [21]; and Johnson Window Films [22]).

The International Glazing Database (IGDB) [23] encompasses the most extensive collection of products used for the construction of windows, namely: different types of glass, films, lamination adhesives, window frames, and filling gasses. It also contains detailed solar optical and thermal information on these products. The addition of products into the IGDB database follows a set of standards issued by the National Fenestration Rating Council. Adding a new film into this database requires that manufacturers provide film samples applied to single uncoated glass substrates with solar and optical transmittances greater than 0.83 and 0.89, respectively. These specifications ensure that the film has transmittance values similar to or lower than those of the glass to which it will be applied to [26]. The glass that meets these criteria is the following: 3 mm single glass; 3 mm single glass with low iron content; and 6 mm single glass with low iron content. Additionally, manufacturers must submit samples of the same glass without the film, so that the thermal and solar optical properties of the glass can be determined separately.

Figure 1 shows the ranges of the thermal and solar optical properties of different types of SCFs, present in the IGDB database [23], when applied to clear single glass (6 mm). The thermal and solar optical properties of these SCFs, when installed in single clear glazing (6 mm), were computed using Optics [24] and Window [25] software. It is possible to note the variety of values for the different properties of the different types of SCF. Reflective and dual reflective SCFs show similar ranges of the main properties' values, except the interior visible reflectance that is significantly lower for dual reflective films. Neutral, spectrally selective and ceramic SCFs show lower reflectance values. Low emissivity SCFs show a noteworthy reduction in the surface emissivity and of the U-value of the glazing system. Safety and protection SCFs show a higher amplitude of values.

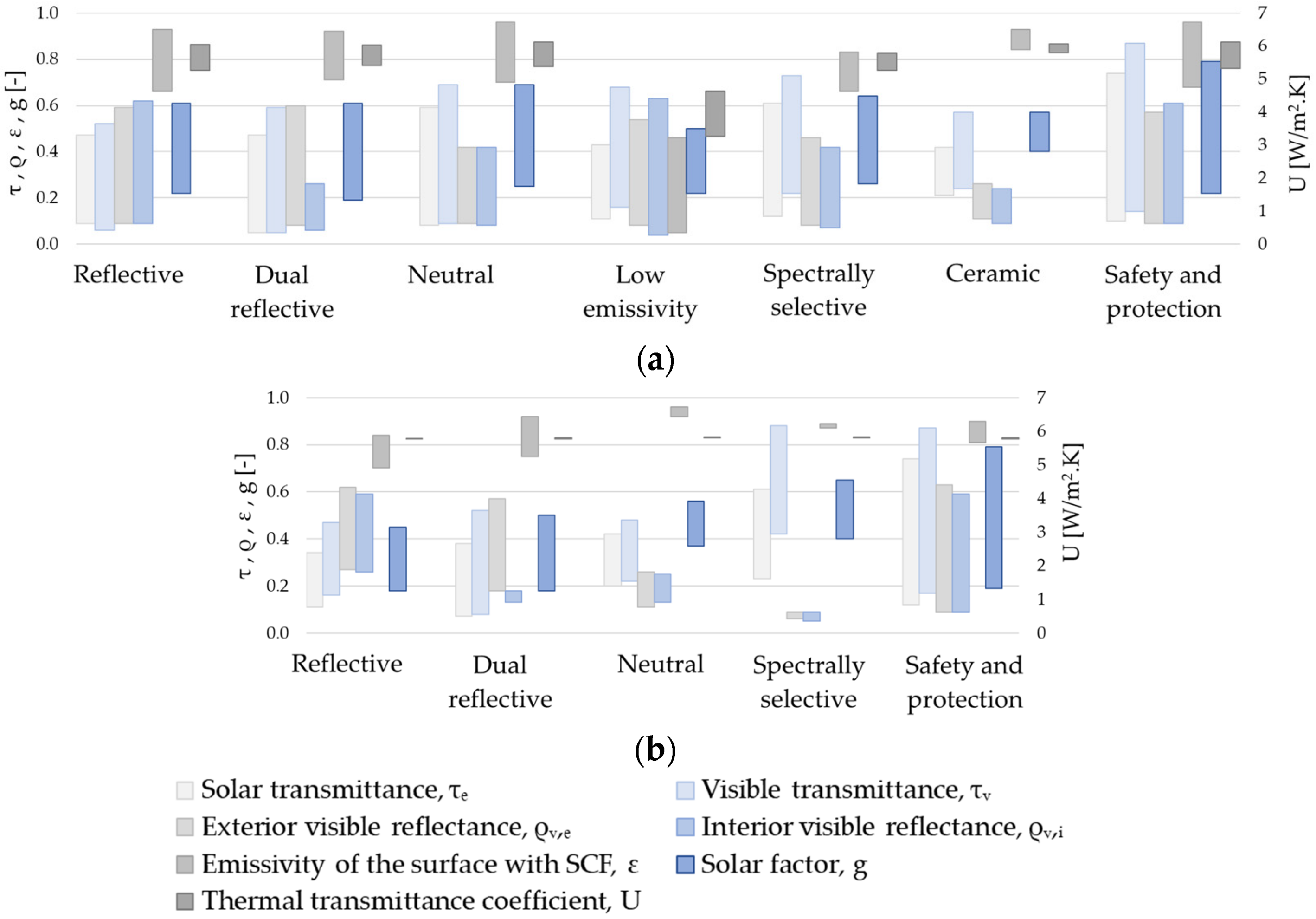

Figure 1. Ranges of values of the thermal and solar optical properties of glass and SCF systems, considering SCF is present in the IGDB database [23] when applied to the internal (**a**) and external (**b**) surface of a clear single glass (6 mm).

2.2. Impact of Solar Control Films on the Main Thermal and Solar Optical Properties of Clear Glass

The performance of SCFs depends on their thermal and solar optical properties, as well as on the properties of the glass substrate to which they have been applied to, as referred in EN 15755-1 [27]. It is important to highlight that there are limitations when SCFs are applied to specific types of glazing due to potential thermal shock breakage of the glass substrate that is usually promoted by the increasing solar absorptance by the film. As a result, a careful analysis should be carried out prior to applying SCFs.

The impact of different types of SCFs on the main thermal and solar optical properties of two glass substrates representative of common building glazing solutions (clear single and double glazing) is assessed. The selected glass substrates are composed of clear glass panes with a thickness of 6 mm and a gas filling chamber with 16 mm of thickness in the case of the double-glazing solution. The SCFs previously assembled were considered for the impact assessment conducted. The ranges of values of the main thermal and solar optical properties of the clear glazing solutions with and without different types of SCFs presented were computed through Optics [24] and Window [25] software.

Figure 2a shows the ranges of values of the main thermal and solar optical properties of clear single-glazing, with and without different types of SCFs applied to the internal glass surface. All types of SCFs made it possible to reduce the solar and visible transmittance values of the glazing, particularly reflective and dual reflective films (by up to 94%). The visible reflectance values increased (up to τv=0.63) in the presence of all types of SCFs. Low-E films drastically reduce the emissivity (lowest ε of 0.05) of the glazing and, consequently, the thermal transmittance coefficient (down to U = 3.26 W/(m^2·K), equivalent to a reduction of 44%) of the window.

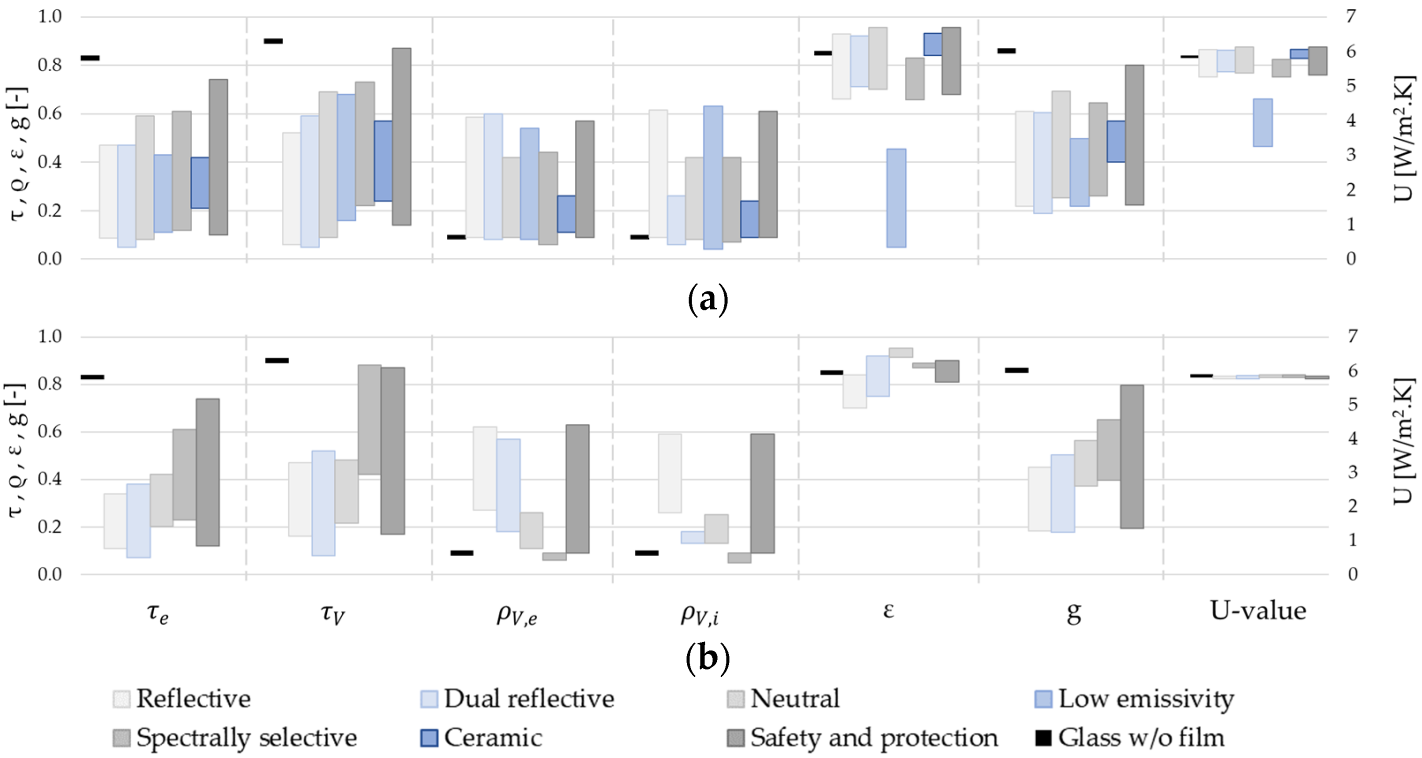

Figure 2. Ranges of values of the main thermal and solar optical properties of clear single glazing with and without different types of SCFs applied to the internal (**a**) and external (**b**) glass surfaces.

Figure 2b shows the ranges of values of the main thermal and solar optical properties of clear single-glazing, with and without different types of SCFs applied to the external glass surface. The types of SCFs with external applications are more restricted than those available for internal applications. The ranges of values of the properties tend to be shorter and tend to include lower values in the presence of SCFs with external application, when compared with SCFs with internal application. However, this could be explained by the scarce number of SCFs with external application. The main properties of the safety and protection SCFs are similar when comparing internal versus external application. The thermal transmittance coefficient remained unchanged with the application of external SCFs.

Figure 3a shows the ranges of the main thermal and solar optical properties values of clear double glazing with and without different types of SCFs applied to the internal glass surface. SCFs modified the values of the properties of the double-glazing in a similar way to that previously observed with the single-glazing (solar and visible transmittance reduced by 94%). However, the application of SCFs to double-glazing did not result in significant reductions in the solar factor (lowest g of 0.31, equivalent to a reduction of 59%) and the thermal transmittance coefficient (lowest U of 1.83 W/(m^2·K), equivalent to a reduction of 32%), as previously obtained with single glazing.

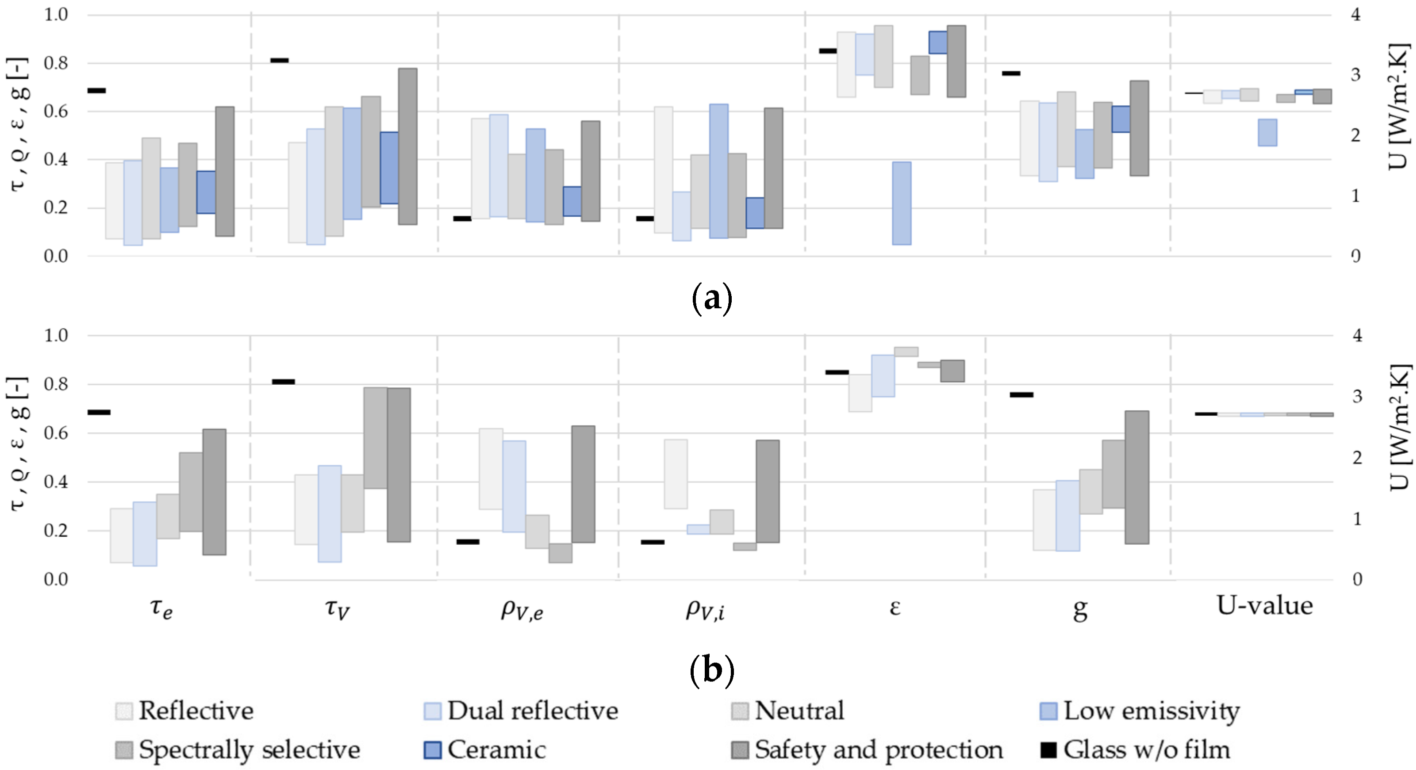

Figure 3. Ranges of values of the main thermal and solar optical properties of clear double glazing with and without different types of SCFs applied to the internal (**a**) and external (**b**) glass surfaces.

Figure 3b shows the ranges of the main thermal and solar optical property values of clear double glazing with and without different types of SCFs applied to the external glass surface. The changes obtained in the presence of SCFs are similar, but of less magnitude than those obtained with single-glazing.

The ranges of values presented in Figure 2 and Figure 3 are relevant to better understand the impact of the different types of SCFs on each clear single and double-glazing property. Selecting the type of SCFs to install in a specific glazing system depends on the solar control purpose (to increase or reduce specific glazing properties) and on the installation position (internal or external). Reflective and dual reflective SCFs should be installed in glazing systems to increase their solar and visible transmittance and, consequently, reduce solar heat gains and potential glare. Neutral, spectrally selective and ceramic films are advised to maintain the neutral appearance of the glazing (lower impact on increasing the reflectance of the glass substrate). Low emissivity films should be installed in cases where the main aim is to drastically reduce the emissivity and U-value of the glazing. The impact of SCFs on the main properties of clear glazing is more noteworthy in the case of the single-glazing substrate.

3. Existing Studies on the Performance of Solar Control Films

A web-based search of existing studies was carried out covering scientific engineering databases such as Science Direct, Scopus and Google Scholar. Very scarce studies have investigated the impact of solar control films (SCFs) on the performance of buildings using numerical [28][29][30][31][32][33][34], experimental [33][34][35][36][37][38][39][40][41][42][43][44][45][46] or computer simulation [29][37][39][40][41][43][44][47][48][49][50][51][52] approaches, singly or in combination.

Table 1 presents a brief description of the existing studies that assess the performance of SCFs installed in building glazing organized by the type of climate (Köppen–Geiger climate classification [53]: Aw, tropical monsoon; Bsk, cold arid steppe; Bwh, hot desert; Cfa, humid subtropical with a hot summer; Cfb, temperate oceanic; Csa, hot-summer Mediterranean; Cwa, monsoon-influenced humid subtropical; Dfb, warm-summer humid continental). These studies generally conclude that the presence of SCFs increases the energy efficiency of buildings and improves the thermal and visual comfort of occupants due to the reduction in extreme solar gains and control of potential glare.

Table 1. Brief description of the type of approach and performance assessment of existing studies on the performance of solar control films.

Climate 1 [53]	Research Studies	Glazing			Research Approach 2			Performance Assessment 3					Comfort Assessment 4	
		Single	Laminated	Double	Num.	Exp.	Sim.	Therm.	Lum.	Energy	Econ.	Envr.	Therm.	Vis.
Aw	Chaiyapinunt et al. (2005) [28]	✓		✓	✓			✓					✓	
Bsk	Yousif (2015) [29]	✓				✓		✓				✓		
Bwh	Al-Taqi et al. (2010) [34]			✓		✓				✓	✓			
	Sedaghat et al. (2020) [46]			✓		✓		✓	✓					
	Noh-Pat et al. (2011) [30]			✓	✓			✓						
	Xamán et al. (2014) [31]			✓	✓			✓						

Climate 1 [53]	Research Studies	Glazing			Research Approach 2			Performance Assessment 3					Comfort Assessment 4	
		Single	Laminated	Double	Num.	Exp.	Sim.	Therm.	Lum.	Energy	Econ.	Envr.	Therm.	Vis.
	Xamán et al. (2017) [32]			✓	✓			✓						
Cfa	Chan et al. (2008) [36]	✓				✓				✓	✓	✓		
	Yin et al. (2012) [47]			✓			✓			✓	✓			
Cfb	Currie et al. (2014) [37]	✓				✓		✓		✓				
	Moretti et al. (2015) [38][48]			✓		✓	✓	✓	✓	✓			✓	✓
	Bahadori-Jahromi (2017) [49]			✓			✓			✓	✓	✓		
	Amirkhani et al. (2019) [50]			✓			✓			✓	✓	✓	✓	
Csa	Pereira et al. (2019) [39]	✓				✓	✓	✓	✓	✓				
	Calama-González et al. (2019) [40]			✓		✓	✓		✓	✓				
	Teixeira et al. (2020, 2021) [41][45]			✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
	Pereira et al. (2020) [38]	✓				✓			✓					✓
	Pereira et al. (2021) [51]			✓			✓			✓	✓	✓		
Cwa	Li et al. (2004) [42]					✓			✓	✓				
	Li et al. (2008) [43]					✓	✓		✓	✓				
	Li et al. (2015) [44]	✓	✓	✓		✓	✓	✓		✓				

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SCFs is higher than those that assess the luminous performance. Only a scarce number of studies contemplates both the thermal and luminous performance [37][39][41][45][46][48].

The heat transmission of different types of glass (single and double-glazing: clear, dark tinted, reflective, and low-E), with and without SCFs, were analyzed in view of an analytical study by Chaiyapinunt et al. [28], conducted under a tropical monsoon climate (Aw [53]). The results show that SCFs reduced the thermal gains due to solar radiation

Climate [1] [53]	Research Studies	Glazing			Research Approach [2]			Performance Assessment [3]					Comfort Assessment [4]	
		Single	Laminated	Double	Num.	Exp.	Sim.	Therm.	Lum.	Energy	Econ.	Envr.	Therm.	Vis.
Dfb [29]	Moghaddam et al. (2021) [52]			✓			✓	✓		✓	✓		✓	

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in a south-oriented glazing system of two wood cells under the cold arid steppe climate of Iraq (Bsk [53]). A reduction in the peak indoor air temperature of 11.5 °C at 2.00 pm (from 68.5 °C to 57 °C) and a reduction of 10–90% of the solar irradiance transmitted through the glazing were obtained.

The thermal performance of SCFs under the hot desert climate (Bwh [53]) was analyzed by Sedaghat et al. [46] and Xamán et al. [30][31][32]. The performance of neutral SCFs installed in double glazed windows of office rooms, in actual working conditions, was experimentally assessed during summer by Sedaghat et al. [46]. The presence of SCFs made it possible to preserve indoor relative humidity levels and decrease the indoor air temperature by 2 °C to 5 °C. When analytically analyzing the performance of a double-glazing system with and without an SCF installed in hot and cold climates, Xamán et al. [30][31][32] concluded that the application of the SCF on double-glazing reduced solar gains through the glazing by 52% and 10% in hot and cold climates, respectively. Due to the results, the researchers strongly recommend using an SCF in hot climates and using reversible windows with SCFs in temperate climates.

Some of the existing studies [36][37][48] evaluated the thermal and luminous performance of SCFs under the temperate oceanic climate (Cfb [53]).

A study by Currie et al. [36] analyzed the installation of blinds against the application of a low-E SCF as rehabilitation solutions to reduce solar gains in a 18th century building in Scotland. Even though the thermal transmission coefficient in the presence of blinds (1.1 W/m^2·K if fully closed) was lower than the value calculated for a window with an SCF, the luminous comfort and the outdoor view would be compromised due to the almost closed position of the blind. The researchers concluded that the SCF had a slightly better performance than the blinds to maintain a balance between the thermal and luminous comfort and take advantage of the benefits inherent to solar gains.

Moretti et al. [37][48] analyzed, experimentally and numerically, the performance of a double-pane window in the southwest façade with and without a reflective SCF, using two similar offices in Italy as a case study. The mean and peak values of incoming solar radiation were reduced by 46% to 66% in the presence of the SCF, resulting in a reduction in the glass surface temperature by 10 °C and the indoor air temperature by 2 °C on sunny days without climate control. Indoor illuminance levels decreased by 50% to 60% during sunny and cloudy days, respectively, in the presence of the SCF.

The performance of SCFs when installed in single- and double-glazing systems of office rooms in Portugal (hot summer, Mediterranean climate (Csa [53])) was assessed by Pereira et al. [39] and Teixeira et al. [41][45], respectively. The researchers concluded that external reflective films have a better thermal performance.

Also, considering a hot summer, Mediterranean climate (Csa [53]), Calama-González et al. [40] assessed the performance of a double-glazed window with and without a reflective SCF installed on the exterior glass surface by monitoring a southwest-oriented hospital room located in Spain. An experimental campaign was conducted throughout a whole year considering real operation and use conditions. The SCF made it possible to reduce indoor illuminance levels by 46.3%.

Li et al. [42][43] experimentally and numerically assessed the performance of SCFs installed in the glazing systems of office rooms in Hong Kong, under a monsoon-influenced, humid subtropical climate (Cwa [53]). A reduction in solar gains of up to 30% was obtained when considering only the diffuse component of solar radiation, and above 50% when considering the direct component [42]. The film drastically reduced the occurrence of high illuminance levels (>5.5 klx) by 30% on sunny days.

Also, considering the monsoon-influenced, humid subtropical climate (Cwa [53]), Li et al. [44] conducted an experimental study in two test cells with different combinations of glazing systems and SCFs facing southwest. The researchers reported that installing SCFs on single glass induces higher indoor glass surface temperatures for clear glass (increase of up to 10 °C) than for tinted or laminated clear glass, proving the higher ability of solar films in absorbing and reflecting radiation when applied to clear glazing.

The only research study that addresses the performance of SCFs in a cold climate (warm summer, humid continental climate (Dfb [53])) was conducted by Moghaddam et al. [52]. The researchers assessed the performance of low-E films installed in double-glazing systems of a building, concluding that the films reduced heat loss through the glazing in winter and unwanted heat gains in summer by almost 36% and 35%, respectively.

3.2. Energy, Economic and Environmental Performance Assessment of Glazing Systems with Solar Control Films

Even though the energy performance of SCFs is commonly evaluated, there are scarce studies that investigate the economic and environmental performance of building glazing with SCFs.

Al Taqi [34] assessed the performance of an SCF installed in a residential building located in a tropical monsoon climate (Bwh [53]). The film reduced the peak cooling demand by 7% and the peak energy consumption of the climate control system by 5%. Even though annual energy consumption was significantly reduced, the high local costs of electricity contributed to extending the payback period (over 40 years).

Chan et al. [35] assessed the performance of hotel rooms with and without an SCF installed on the glazing under a humid subtropical with a hot summer climate in China (Cfa [53]). The researchers obtained annual energy savings of 155 kWh due to the reduction in cooling energy needs. Considering different scenarios for a cost–benefit analysis, a payback period of between 3.5 and 4.7 years was obtained.

In addition, in a humid subtropical climate, Yin et al. [47] simulated the energy performance of the double-glazing of a museum building with and without SCFs. Building cooling energy savings between 44% and 56% were obtained due to the reduction in solar transmittance, having achieved an average reduction in the cooling needs of about 50%. Even with the increased heating needs with SCFs, the energy efficiency of the building improved.

A whole building performance evaluation in the presence of SCFs was conducted by Currie et al. [36], Bahadori-Jahromi [49] and Amirkhani et al. [50] under a temperate oceanic climate (Cfb [53]).

Currie et al. [36] assessed the performance of a low-E film against the installation of blinds as solutions to reduce solar heat gains in a 18th century building located in the temperate oceanic climate (Cfb [53]) of Scotland. After conducting experimental work, a best-case model was simulated, and a reduction of 30% of the heating energy cost was obtained, in addition to a significant reduction in carbon dioxide emissions due to heating energy consumption.

The performance of spectrally selective and low-E SCFs, when installed in a hotel in a temperate climate, was studied by Bahadori-Jahromi [49] and Amirkhani et al. [50]. Heating and cooling energy consumption was reduced by 3% and 20% in the presence of low-E films. Even though spectrally selective films are more effective in reducing cooling energy consumption, low-E films were found to be a better solution for the heating-dominated climate of the case study.

Also, considering the temperate oceanic climate, the performance of double-glazing, with and without SCF, in office rooms in Italy was studied by Moretti et al. [37][48]. The researchers concluded that the reduction in the indoor temperature due to the application of the film resulted in the reduction in the cooling needs of between 29% and 40%. However, an increase in the heating needs of between 15% and 33% was obtained, particularly during the heating season.

The energy performance of SCFs applied to glazing systems of a hospital room and office rooms under the hot-summer Mediterranean climate was evaluated by Calama-González et al. [40] and Pereira and Teixeira et al. [39][41][45], respectively.

Calama-González et al. [40] evaluated the performance of an external reflective film installed in a glazing system of a hospital room located in the hot-summer Mediterranean climate (Cfa [53]). The combined use of the film with shading shutters reduced artificial lighting energy consumption by 12%. The presence of the film during winter penalized energy consumption.

Pereira et al. [39] and Teixeira et al. [41][45] analyzed the performance of different SCFs installed in the single- and double-glazing systems of office rooms in the hot-summer Mediterranean climate of the city of Lisbon (Csa [53]). Reflective films were found to have a better energy performance, with a significant reduction in the cooling energy consumption that surpasses energy increases with artificial lighting. The annual energy use was reduced by 68% and 38% when considering the installation of SCFs in single- and double-glazing, respectively, oriented south.

Considering a whole building performance evaluation, also in the climate of Lisbon, Pereira et al. [51] assessed the energy, economic and environmental performance of SCFs (one reflective and two spectrally selective) against the replacement of the existing window. Higher energy savings during the use stage were obtained in the presence of the retrofitting solutions with higher light-to-solar gain ratios because of the higher reduction in solar gains compared with the reduction in the visible transmittance. The spectrally selective film with high solar transmittance was found to be the best retrofitting solution with a life cycle energy (including embodied and operational energy) and a carbon footprint of 4447 MJ and 380 $kgCO_2eq$ per square meter of floor, considering a life cycle of 40 years. The replacement of the existing window showed a life cycle energy 1.5 times higher than the average values obtained for the different SCFs.

The energy performance of SCFs installed in building glazing systems under a monsoon-influenced humid subtropical climate (Cwa [53]) was evaluated by Li et al. [42][43] and Li et al. [44].

The performance of office spaces located in Hong Kong (monsoon-influenced humid subtropical climate (Cwa [53])), with and without SCFs, was evaluated by Li et al. [42][43]. Considering single-cell office rooms, the daily cooling energy consumption was reduced by 68 Wh per square meter of floor in the presence of the film, whereas the artificial lighting consumption increased by 13 Wh/m^2 of floor, resulting in total energy savings of 55 Wh/m^2 of floor [42]. Considering an open-plan office space with dimmable lighting controls and an SCF installed on the glazing system, artificial lighting and cooling energy savings of about 21% and 7%, respectively, were obtained.

Also, in the climate of the city of Hong Kong, Li et al. [44] evaluated the energy performance of different types of buildings (office, shopping center and hotel room) through a computer simulation model, considering glass and film systems previously experimentally assessed. The researchers obtained annual energy savings between 77 and 90 kWh per unit area of SCF installed in the west-oriented single-glazing of an office space. Regarding the shopping center and hotel room, annual energy savings between 44 and 57 kWh per unit area of SCF were obtained.

Considering the warm-summer humid continental climate (Dfb [53]), Moghaddam [52] analyzed the performance of low emissivity films applied to double-glazing. The application of SCFs made it possible to reduce the annual energy consumption of the building for heating by 6%. However, when performing a life cycle cost analysis, the researchers concluded that the high price of the low-E films and the contrasting low price of district heating resulted in an extremely long payback period of 30 years.

3.3. Comfort Assessment of Glazing Systems with Solar Control Films

A scarce number of the existing studies assess the thermal [28][37][41][45][48][50][52] and visual [37][38][41][45][48] comfort in the presence of SCFs installed in building glazing systems. Some studies evaluated both the indoor thermal and visual comfort, considering the same case study [37][41][45][48], to help differentiate the thermal and visual impact of SCFs. Comfort assessment has been scarcely explored in real occupancy conditions using experimental data, with the majority of the studies conducting computer simulation analyses.

Chaiyapinunt et al. [28] used the predicted percentage of discomfort (PPD) values, due to the solar radiation effect and glass surface temperature, to evaluate thermal comfort in the presence of different combinations of glazing and SCFs, under a humid tropical climate (Aw [53]). The analysis and comparison, considering these different combinations of glazing and SCFs, are of high importance as background information and to help guide/predict the performance of existing scenarios. All glazing, with or without films, except for reflective glazing, showed that the PPD due to solar radiation was higher than the PPD due to the glass surface temperature.

Moretti et al. [37][48] evaluated the thermal and visual comfort of a reflective SCF applied to the double-glazing of an office room located in a temperate oceanic climate (Cfb [53]). Even though occupants still feel warm/hot in the office with SCF during summer, according to the computed PMV values, the reflective film made it possible to reduce the PPD values by 20–50% when compared with the office room without SCF.

Amirkhani et al. [50] evaluated the thermal comfort of a building with low-E films by analyzing indoor operative temperature values, computed using a simulation model. During summer, the low-E films reduced the percentage of hours with excessive temperature levels (higher than 25 °C) by 5% compared with the original clear glazing.

Teixeira et al. [41][45] assessed the thermal and visual comfort of office rooms with double-glazing with different types of SCFs, under the hot-summer Mediterranean climate (Csa [53]) of the city of Lisbon. This evaluates indoor visual and thermal comfort under real occupancy conditions. A highly reflective solar control film was found to significantly reduce potential glare (43% of working hours with comfortable glare levels) when analyzing the computed daylight glare index values. SCFs increased the percentage of working hours within comfort levels of operative temperature by 25% compared with the original clear glazing (10% of working hours within thermal comfort).

Also, in the city of Lisbon, Pereira et al. [38] experimentally analyzed the indoor illuminance levels and distribution on the horizontal work plane in the presence of south-oriented single-glazing with highly reflective and spectrally selective SCFs. Field experiments were conducted in a small-scale model, under clear sky conditions during summer and winter solstice. SCFs showed a better visual performance in summer, decreasing excessive illuminance levels and promoting a more extensive spatial distribution of acceptable levels of daylight availability. The lower solar altitude during winter, that increased solar radiation perpendicular to the glazing, had a negative impact on the visual performance of SCFs. A highly reflective film was found to be the best solution to provide useful illuminance levels and prevent potential flare. This is relevant to better understand the influence of SCFs on the indoor daylight distribution under clear sky conditions.

Indoor thermal comfort in the presence of a low-E SCF installed in the double-glazing system of a building located in a cold climate was assessed by Moghaddam et al. [52]. PPD values were reduced up to 5% in the presence of the low-E film installed in the northwest and southwest glazing. Even though the low-E film slightly reduced thermal discomfort when installed in the southeast-oriented glazing, the PPD values often surpass the limit value of 10%. The reduction in working hours with thermal discomfort is insufficient for the building to fully meet the existing thermal comfort requirements, so the low-E film should be complemented with other supplementary strategies.

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