The Potential of Static and Thermochromic Window Films for Energy Efficient Building Renovations

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Abstract

The type of glazing implemented in a building plays an important role in the heat management of a building. Solar heat entering through glazing causes overheating of interior spaces and increases building's cooling load. In this work, the energy saving potential of window films based on Cholesteric Liquid Crystals (CLC) is explored. This emerging technology allows for the fabrication of static and thermochromic solar heat rejecting window films and can provide a simple renovation solution towards energy efficient buildings. Simulations on a model office showed that static CLC-based window films can save up to 29% on a building's annual energy use in warm climates. In climates with distinct summer and winter seasons, static solar heat rejecting windows films cause an additional heating demand during winters, which reduces the annual energy savings. In these climates, the benefit of thermochromic CLC-based window films becomes evident and an annual energy saving up to 22% can be achieved.

Keywords

glazing, solar heat rejection, window films, thermochromic, energy savings

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1 INTRODUCTION

The world population and people living in urban areas is growing (United Nations, 2018; 2019). To host and keep hosting this growing population, high-rise buildings are increasingly dominating the city landscape. These buildings should provide comfort and well-being to its occupants, be sustainable and simultaneously positively impact the urban environment. To this end, large glazing areas are increasingly used in building façade designs, as this allows natural daylight, which positively impact the health and productivity of occupants (Chen, Zhang, & Du, 2019; Knoop et al., 2020). However, solar heat entering through glazing causes overheating of indoor spaces and increases the demand for artificial cooling loads. Buildings are already responsible for 36% of worldwide energy consumption. Despite increasing population and floor area, reductions in energy consumption have been realized between 2010 and 2018 for space heating, lighting, appliances, cooking, and domestic hot water. In contrast, the energy use for space cooling has increased by 33% in this period, which is likely related to increased glazing area, rising temperatures, and an increasing demand for thermal comfort, and is expected to increase even further (Glass for Europe, 2019; IEA, 2018). Due to this steep increase in cooling demand, the overall energy consumption of buildings is still increasing at 1 to 2% per year (Dennis, 2018; IEA, 2019; Pérez-Lombard et al., 2008; Prieto et al., 2017). Therefore, it is of increasing importance to implement measures that reduce the energy use for space cooling in the built environment. This need is also recognized by policies which prescribe reduction of CO_2-emissions in the building sector. In view of this, the European Commission aims to at least double the renovation of existing building stock for the next ten years. Therefore, 35 million buildings in Europe should be renovated by 2030 (European Comission, 2020). These regulations have led to an increasing demand for innovative materials to reduce the environmental impact and increase the sustainability of new and existing buildings. In this respect, there is a lot to gain by renovation of existing glazing and glazing designs in new buildings. If all EU buildings were equipped with high-performance glazing by 2030 a total of 29% of energy use can be saved annually. This corresponds to an annual CO_2-emission reduction of up to 94.2 million tonnes (Glass for Europe, 2019).

Thermal losses and heat gains through glazing determines for a large extent the energy consumption performance of a building. On cold days (e.g. in winter), thermal losses from inside to outside a building should be reduced as much as possible to decrease energy use on heating systems. Simultaneously, on warm days (e.g. in summer), solar heat gains through glazing from outside to inside a building should be prevented to reduce the required energy for space cooling (Long & Ye, 2014). Solar radiation contains UV-light (300 - 400 nm), visible light (400 - 700 nm) and near-infrared (near-IR) light (700 – 2500 nm, Figure 1) (Jelle et al., 2015; Rezaei et al., 2017). UV-light has the ability to affect other materials, such as furniture inside a building, causing discolouration and degradation and interacts with the human skin with a potential negative impact on people's health (Gonzaga, 2009; Kim & Kim, 2010). Therefore, a window element or material should preferably block UV-light. The visible light part of the spectrum accounts for 43% of the solar energy. Interaction of a window with this part of the solar spectrum will determine the tinting or colouring of a window and therefore the appearance of the building and the daylight comfort of its occupants. The near-IR light accounts for 52% of the solar energy and causes heating of interior spaces. Therefore, glazing technologies that focus on the reduction of solar heat gains through glazing focus on rejection of solar near-IR light, while allowing sufficient visible light to ensure daylight comfort.

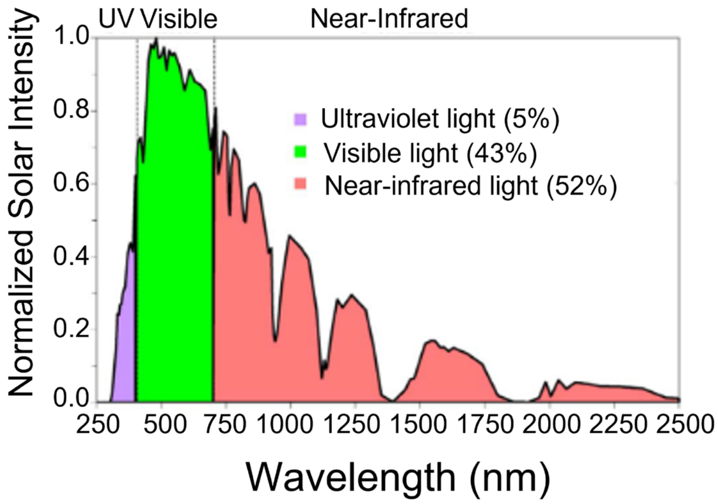

FIG. 1 The solar energy distribution. Adapted from Rezaei et al., 2017

Various glazing solutions are developed to impact the heat management of buildings. Next to shutters and blinds, a common solution is the use of low-emissivity (Low-E) coatings. Such Low-E materials usually consist of various layers of metals (typically silver) and metal oxides, which can for instance be applied to a glass pane via sputtering or other deposition techniques (Ding & Clavero, 2017; Jelle et al., 2012). Their main function is to re-direct long-wave radiation from inside a building back into the building to reduce the amount of heating required on cold days. These coatings thus increase the insulating properties of a glazing units (Long & Ye, 2014). In addition, various Low-E coatings exist which not only insulate glazing, but also reject solar heat to keep a building cool on warm days and reduce the energy use on artificial cooling (Al-Obaidi et al., 2014; Jelle et al., 2015; Mohelníková & Altan, 2009; Rezaei et al., 2017; Xu et al., 2017). Nowadays, most new building designs in cold or temperate climates are equipped with Low-E coated insulating glass units (IGUs) (Selkowitz, 1999).

Another solution that reduces the solar heat gains through glazing is the use of solar heat rejecting window films. Such films are simply adhered to existing IGUs to upgrade a building's glazing performance without the need to replace any glass panes (Bahadori-Jahromi et al., 2017; Curcija et al., 2017). Window films can be fabricated via roll-to-roll methods on flexible substrates at high throughput. Over the years, companies in this field, such as 3M and Saint-Gobain, developed a variety of window films having various gradations of tinting and near-IR reflection based on reflective metal-containing coatings or absorptive metal oxides (Jelle et al., 2015; Kim et al., 2021). These films are designed and optimized for various climates around the world. For instance, a warm and sunny climate requires a film with more tinting and near-IR reflection, whereas a colder and less sunny climate requires more visible light transmission and less near-IR reflection, in order to optimize the balance between solar heat gains in winter and rejection in summer (Hui & Kwok, 2006; Li et al., 2015; Sedaghat et al., 2021). As such films are fabricated in a cost-effective way and can be applied to existing window panes, they are an appealing and easy-to-install renovation option.

Low-E coated glazings and solar heat rejecting window films do not adapt their optical properties with the outdoor weather conditions. In winter, when solar heat is desired to enter a building, these solutions also reject solar heat, causing an additional energy use on heating the indoor space to a comfortable temperature. Therefore, climates with distinct summer and winter seasons would benefit from dynamic glazing solutions (Casini, 2014). Several pilot and simulation studies revealed that such dynamic glazing solutions could realize an annual energy saving between 8 and 53% in temperate climates compared to traditional glazing solutions depending on variables, such as building geometry, orientation, and the used reference glass (General Services Administration, 2014; Khandelwal et al., 2015; Mann et al., 2021; Mann et al., 2020; Dussault et al., 2012; DeForest et al., 2017). A recent development is the electrically switchable glazing. These glazings can be switched from a transparent to tinted state on demand of the end-user or coupled to a sensor to tint autonomously depending on the outdoor sunlight intensity (Al Dakheel & Aoul, 2017). These systems are effective in maintaining a comfortable light illumination throughout the day and also allow an energy benefit compared to non-responsive glazing units (Arbab et al., 2017; Clear et al., 2006; Day et al., 2019; General Services Administration, 2014; Mardaljevic et al., 2016; Painter et al., 2016; Piccolo & Simone, 2009). Electrically switchable materials can be prepared from electrochromic metal oxides, such as tungsten oxide (WO_3), but also include examples of conjugated polymers and switchable liquid crystal (LC) devices (Baetens et al., 2010; Casini, 2018; Ke et al., 2019; Khandelwal et al., 2015; Khandelwal et al., 2017; Marchwinski, 2014; Wang et al., 2016). The fabrication of these systems requires sandwiching of the responsive material between two glass plates with electrically conductive layers and requires electronic wiring, which causes high fabrication and installation costs (Brzezicki, 2021). Dynamic glazing solutions that require a simpler installation are systems that respond autonomously to outdoor weather conditions, such as thermochromic glazing solutions (Mann et al., 2020; Seeboth et al., 2010; Serpe, 2019). These materials can consist of inorganic pigments that can change their absorptive properties with temperature, such as VO_2-based thermochromic materials (Calvi et al., 2021; Cui et al., 2018; Ke et al., 2018; Long & Ye, 2014; Yeung et al., 2021). These systems are usually laminated between two glass plates and are installed similar to regular IGUs.

This work discusses the energy saving potential of an emerging technology, namely Cholesteric Liquid Crystal (CLC) based coatings, for solar heat management in buildings. LCs are materials that possess both solid-like as well as liquid-like properties. LC molecules have some level of organisation similar to the crystal structure of a solid, but are also able to change organisation easily and flow like a liquid. When incorporating a chiral molecule inside an LC, a rotation in the molecular organisation can be induced and a periodic helical organization of the molecules can be created, called a CLC phase (Figure 2) (Liang, 2015). This helix provides an optical structure with periodically altering refractive indices, which is able to reflect light of a specific wavelength and circular polarization. Therefore, a CLC material can reflect 50% of incoming unpolarized light around a specific central wavelength. This wavelength is determined by the periodicity of the cholesteric helix structure, which can be tuned by the concentration and type of chiral dopant (Balamurugan & Liu, 2016; Dierking, 2014; Liu et al., 2016; Mitov, 2012; White et al., 2010). A CLC material can thus be tuned to reflect only in the near-IR range of the solar spectrum, while leaving the visible light transmission unaffected. This property makes them appealing as solar heat rejecting glazing material. Furthermore, the wavelength range to be reflected can be broadened to lower the solar heat gain coefficient (SHGC) of the glazing. This can be achieved by coating multiple CLC layers reflecting at different wavelengths on top of each other, but might also be achieved by creating a pitch gradient in a single CLC layer (Khandelwal et al., 2014; Kim et al., 2018; Liu et al., 2016; Mitov, 2012; Ranjkesh & Yoon, 2021; Van Heeswijk et al., 2019). Such a pitch gradient might be achieved by polymerization induced diffusion methods, in which one creates a concentration difference of the chiral dopant throughout the thickness of the CLC material (Broer et al., 1999; Fan et al., 2008; Khandelwal et al., 2017). Another possible route could be the stepwise polymerization at various specific temperatures of a thermochromic CLC material (Duan et al., 2017; Guo et al., 2010; Mitov et al., 2004; van Heeswijk et al., 2020; Wu et al., 2011; Xiao et al., 2016). In this way various pitch lengths, and thus reflective wavelengths, are established inside one CLC layer. Using these methods, CLC broadband reflectors spanning a wavelength range of up to 13 μm have been fabricated (Zhang et al., 2016). To decrease the SHGC further, the 50% reflection limit of a regular CLC-based device can be exceeded by including both a left- and right-handed helical CLC structures into one window film device (Khandelwal et al., 2014; Mcconney et al., 2011; Ranjkesh & Yoon, 2021; Zhao et al., 2015). Another option would be to insert an achromatic optical half-waveplate material in between two broadband CLC reflectors of the same handedness (Komanduri et al., 2013; Kraemer & Baur, 2019; Ortiz-Gutiérrez et al., 2001). Such a waveplate converts the transmitted circularly polarized light of the first CLC broadband layer to the opposite handedness, which then can be reflected by the second CLC broadband layer (Khandelwal et al., 2014; Kragt et al., 2019; Mitov, 2012).

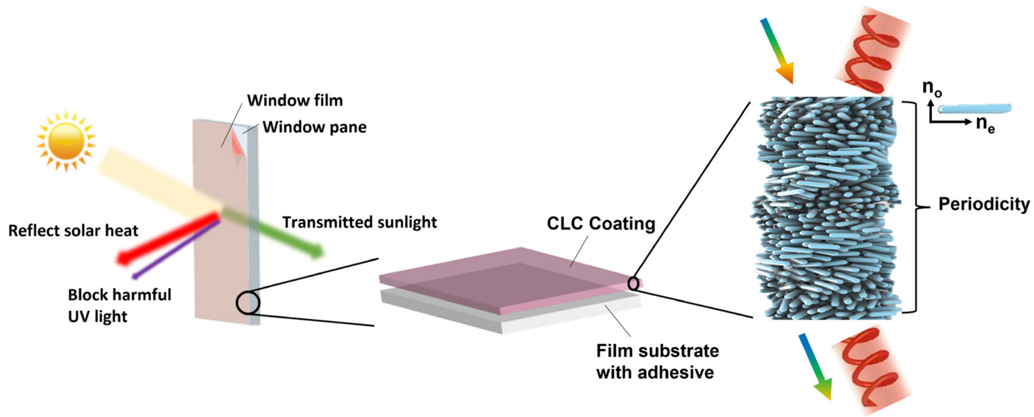

FIG. 2 Simplified representation of a solar heat rejecting window film based on a CLC reflective coating. (left) A solar heat rejecting window film adhered to glass. (middle) A zoom-in on a simple window film build-up comprising a CLC coating on an adhesive film substrate. In practice, the window film might consist of multiple coating layers bearing various functionalities. (right) A representation of the periodic helix structure inside a CLC coating. The molecules are represented by the blue bars. The periodic rotation of the extraordinary and ordinary refractive indices (ne and no, respectively) causes the CLC material to reflect light of a specific wavelength and circular polarization. Many of these periodic helices are present in one coating layer to reach the 50% reflection limit of a single CLC coating layer. The CLC helical structure is adapted from Liang, 2015.

Besides static reflectors, the organisation, and thus optical properties of CLC materials, can also be tuned by external stimuli, such as electric fields and temperature (Khandelwal et al., 2017; Zhang et al., 2021). This property also makes them appealing for dynamic glazing solutions that can respond to outdoor weather conditions. By modifying the chemical composition and processing conditions CLC-based materials can be fabricated that can, for example, shift their reflective wavelength upon changes in temperature (Khandelwal et al., 2019; Kragt et al., 2019; Ranjkesh & Yoon, 2019; White et al., 2010; Zhang et al., 2021). In particular, CLC materials that show a phase transition from a non-reflecting smectic liquid crystal phase to a reflective cholesteric phase are prone to show huge wavelength shifts towards lower wavelengths upon increasing the temperature (van Heeswijk et al., 2019; Yang et al., 2022; B. Zhang et al., 2019; P. Zhang et al., 2018; W. Zhang et al., 2017; Zhang et al., 2021). In a smectic phase the molecules are organized in a two-dimensional order, not bearing the periodic helical structure of a CLC phase. As soon as the material undergoes a phase transition from a smectic to a cholesteric phase, the cholesteric pitch starts to form and gradually becomes shorter, causing a shift of the reflective properties towards smaller wavelengths. Such materials have shown reflection band shifts of over 1100 nm (Tzeng et al., 2010). The transition temperature and reflective wavelength position of such materials can be tuned by varying the chemical composition of the thermochromic CLC material. In addition, one could even design a material that is able to shift from a narrow to broadband reflector by partly polymerizing a thermochromic material (Khandelwal et al., 2016; Yang et al., 2003; Yuan et al., 2010). In this way, CLC-based materials can be used to regulate the level of solar heat rejection based on the outdoor temperature conditions.

In this work, the energy saving potential of both static and thermochromic CLC-based window films in both warm and temperate climates is explored. The window films are based on a CLC coating applied on a flexible substrate providing a static near-IR reflecting film that can be adhered to a glass plate (Figure 2). Such window films are interesting for energy efficient building renovations. The impact on a building's energy consumption when developing these films into a full broadband reflector and thermochromic window film is evaluated using an office building simulation. This provides insights on further material developments towards effective energy saving window film products based on CLC coating technology.

2 METHODOLOGY

To explore the potential impact of CLC-based window film technologies on the energy performance of a building various static and thermochromic window films are designed to represent the theoretical optical performance limits of CLCs. The glazing characteristics, such as visible light transmission (T_{vis}), solar heat gain coefficient, (SHGC) and U-value, of these window films in combination with a double clear IGU and a Low-E coated IGU are calculated. These glazing characteristics are then used to specify the glazing performance of a building model in DesignBuilder representing a standard office floor. The monthly and annual energy use for lighting, heating, and cooling of this building is calculated and the energy performances with various glazings inserted are compared to each other to quantify the energy saving potential of the CLC-based window films.

2.1 CHOLESTERIC LIQUID CRYSTAL WINDOW FILMS

Several static window films, as well as one thermochromic window film, are designed based on empirical findings during laboratory fabrication and methods described in literature. For the CLC-based window film that is actually fabricated in a laboratory, the film is adhered to a single glass pane and the optical properties are measured by spectrophotometry. This data is imported in LBNL software Optics6 to determine its optical characteristics and subsequently in Window 7.7 to translate these to glazing characteristics. For the CLC-based window film designs that are based on methods described in literature, the transmission and reflection spectra are not measured, but plotted by hand. In this process realistic values for reflection band broadness and depth are taken based on findings in literature representing the limits of CLC-based technology. For the thermochromic window film design potential transition temperatures and wavelength shifts found in literature are taken as a reference. These simulated optical data are then imported similarly as the actually fabricated CLC-based window film into the LBNL softwares Optics6 and Window 7.7 to determine the glazing characteristics.

The optical properties of Cholesteric Liquid Crystals (CLCs) can be custom designed by using various processing methods. The first CLC-based window film design consists of a single CLC coating layer on a polyethylene terephthalate (PET) substrate based on a CLC ink formulation provided by ClimAd Technology and is actually fabricated in a laboratory. This ink was coated on a UV-blocking polyethylene terephthalate (PET) film having a thickness of 50 µm by means of wire-bar coating and subsequent drying and UV-curing steps. An optically clear adhesive was laminated at the non-coated side of the film, which was then adhered to a 4 mm thick single clear glass plate (10 x 12 cm, Stolker Glas). The transmission spectrum of this window was measured on a Perkin Elmer Lambda 750 UV/Vis/NIR spectrophotometer over a wavelength range between 400 and 2500 nm (Figure 3A, black solid curve, CLC narrow). In addition, the reflection spectra of the glazing device were measured from both sides of the sample over the same wavelength range. The CLC narrow band window film device has a central reflective wavelength at 920 nm at which it reaches a transmission of 48%. Adhered to a single clear glass plate, the CLC narrow band window film has a visible light transmission of 88% and a solar heat gain coefficient (SHGC) of 0.79 as determined with LBNL software Optics6 and Window7.7.

The SHGC of CLC-based window films can be decreased by broadening the reflection band of the CLC material (Liu et al., 2016; Mitov, 2012). To explore the energy saving potential of such broadband reflectors, transmission and reflection spectra were plotted by hand. The depth of the transmission spectrum in the reflected wavelength range as well as the baseline of a single glass pane is based on the measured spectra of the actually fabricated CLC narrow band window film device. The bandwidth of the plotted broadband CLC-based window film device reflected a full width at half height between 840 and 1570 nm. (Figure 3A, yellow curve, CLC broad). Broadband reflectors spanning a similar or even larger wavelength range are also described in literature and can be fabricated by creating a pitch gradient in a single CLC material layer by polymerization induced diffusion methods or by polymerizing a thermochromic CLC material at various temperatures (Fan et al., 2008; Duan et al. 2017; Xiao et al., 2016; L. Zhang et al., 2016). Therefore, the chosen wavelength range of the simulated broadband CLC-based window film device is believed to be feasible in practice when optimized as a coating on a window film. Adhered to a single clear glass this device has a SHGC of 0.72, while the visible light transmission is still at 88%. To decrease the SHGC of CLC-based window films further one could fabricate a broadband reflector exceeding the 50% reflection limit of a single layer of CLC material by superimposing multiple layers of opposite handedness of the CLC helix structure or sandwiching a half waveplate material in between two CLC layers reflecting similar handedness (Khandelwal et al., 2014; Komanduri et al., 2013; Kraemer & Baur, 2019; Kragt et al., 2019; Mcconney et al., 2011; Mitov, 2012; Ortiz-Gutiérrez et al., 2001; Ranjkesh & Yoon, 2021; Zhao et al., 2015). In this way, CLC-based reflectors are created, reflecting nearly all incoming light within the reflected wavelength range. Therefore, the third static CLC-based window film device used in this work consists of two CLC-based broadband reflectors superimposed on top of each other to create a broadband reflector that reflects nearly all incoming light. This design represents the limits of CLC-based window films that could be achieved in practice after optimization. This simulated full broadband reflector reflects over the same wavelength range as the simulated broadband reflector described above, but reaches a transmission as low as 5% over the reflected wavelength range (Figure 3A, green curve, CLC full broad). Adhered to a single clear glass plate this CLC-based window film device reaches a SHGC of 0.54 with a visible light transmission of 85%.

CLC materials not only allow for the fabrication of static IR reflectors, but could also be processed to thermochromic devices (Khandelwal et al., 2016; Tzeng et al., 2010; van Heeswijk et al., 2019; Yang et al., 2022; Zhang et al., 2018; Zhang et al., 2021). To simulate the potential limits of thermochromic CLC-based window film we combined several literature findings into one design. This design is based on CLC materials that show large reflection band shifts spanning hundreds of nm in a temperature range between 12 and 20 °C (Tzeng et al., 2010; Yang et al., 2022). By applying a processing method in which such thermochromic CLC material is only partly polymerized one could create a device that is changing from a narrowband to a broadband upon increasing the temperature, as the thermochromic response of the polymerized portion of the material is inhibited, while the non-polymerized part still shifts its reflected wavelength (Khandelwal et al., 2016; Yang et al., 2003; Yuan et al., 2010). Similar to the simulated static full broadband reflector design, two such thermochromic CLC layers could be superimposed on top of each other to fabricate a thermochromic CLC-based window film reflecting nearly all incoming light over the reflected wavelength range.

Combining these materials and methods described in literature and optimizing those into a single device, one could imagine a thermochromic CLC-based window film that is not reflecting at 10 °C, turns into a full narrowband reflector at 12 °C, and gradually changes to a full broadband reflector at 20 °C. The spectral data of such a thermochromic window film on a single glass pane are plotted by hand in which the baseline is based on the actually measured glass pane subtracted by the overall absorption one could expect from two CLC coating layers based on the actually measured static CLC narrow band window film. For a fair comparison between the static and the thermochromic window film device, the thermochromic window film starts to reflect a narrowband at 1500 nm at 12 °C and turns into a full broadband reflector at 20 °C, covering the same wavelength range as the static CLC-based window film design (Figure 3B). These simulated spectral data at the various temperatures are imported into the LBNL softwares Optics6 and Window 7.7. The SHGC of the thermochromic CLC based window film changes instantly and reversibly from 0.82 to 0.79 to 0.54 as soon as the temperature of the thermochromic coating layer is altered from 10 to 12 to 20 °C, respectively, by daily fluctuations of outdoor air temperature and solar radiation. The visible light transmission of the thermochromic CLC based window film remains unchanged (85%) at the various temperatures.

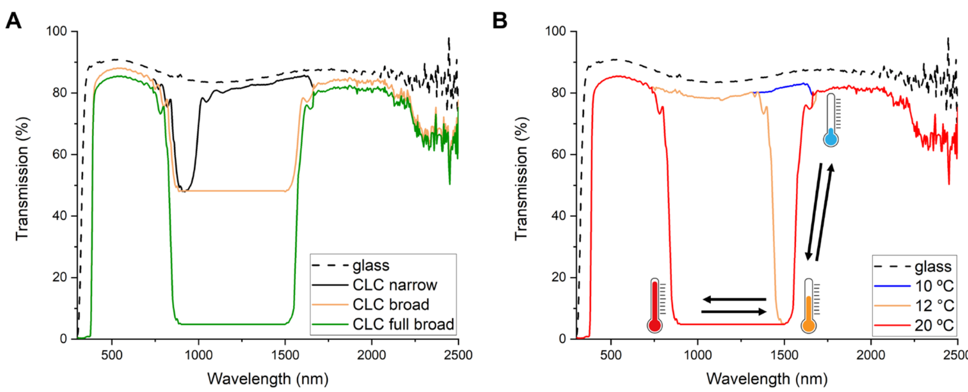

FIG. 3 Transmission spectra of static CLC-based window films adhered to a single clear glass plate (4 mm) of (A) various static window films and (B) a thermochromic window film. The CLC narrowband reflector film is measured from a fabricated sample. The other data are derived from this spectrum and represent the potential of CLC-based window film technology.

2.2 GLAZING DESIGN CHARACTERISTICS

Two IGUs were selected as reference glazing systems; a double clear glass system and a Low-E coated glass system. The glass characteristics of the clear glass were calculated by importing transmission and reflection spectra of a 4 mm glass plate (Stolker Glas) in the LBNL software Optics6. The glass characteristics of the Low-E coated glass were taken from the International Glazing Database (Saint-Gobain Eclaz 4 mm). The IGU glazing characteristics were calculated in the software DesignBuilder according to ISO 10292 and consisted of two glass plates (clear or Low-E coated) filled with argon (16 mm). The Low-E coating was placed on the inner side of the inner glass pane (position 3). The double clear and Low-E coated IGUs were equipped with CLC-based window films by replacing the outside glass pane with a user-defined glazing defined by the glazing characteristics as calculated in the previous section, so that the window film faces the outdoor environment (position 1, Figure 4). For the thermochromic CLC-based window film the outside glass pane has to be defined as a 'pane group' instead of a static 'pane'. Within this pane group the glazing characteristics of the glazing at different temperatures can be defined in a similar way as for a static glass pane. The calculated glazing characteristics of the double clear and Low-E coated IGUs equipped with various CLC-based window films are tabulated in Table 1 and Table 2, respectively. In practice, the window film might also be integrated inside the IGU unit (e.g. position 2) or integrated as a laminate between two glass plates. The glazing characteristics could be somewhat affected in these configurations, but this is beyond the scope of this work.

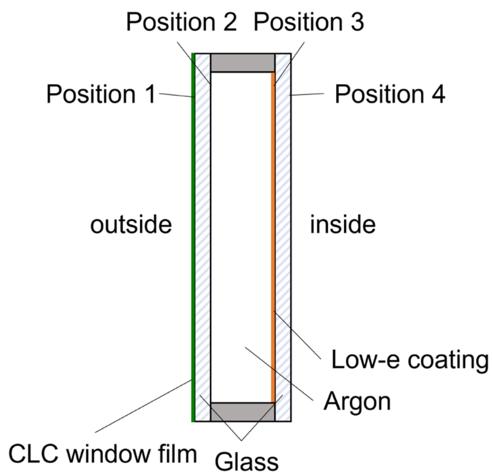

FIG. 4 Schematic build-up of the Low-E coated IGU equipped with a CLC-based window film

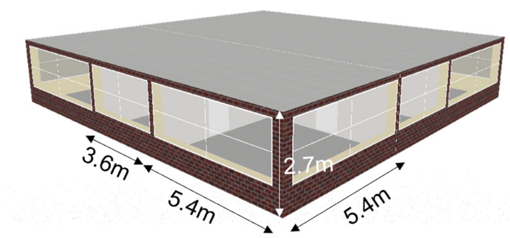

FIG. 5 Schematic representation of the model office used in the DesignBuilder simulations

TABLE 1 **Glazing characteristics of double clear IGU equipped with various CLC window films.**
The SHGC for the thermochromic window glazing system is given at various temperatures (10, 12, and 20 °C).
The visible light transmission remains constant at various temperatures.

glazing type	Double clear	+ CLC narrow	+ CLC broad	+ CLC full broad	+ thermochromic
Tvis (%)	83	80	80	78	78
SHGC	0.79	0.71	0.65	0.50	0.73 > 0.71 > 0.50
U-value (W/(m2K))	2.6	2.6	2.6	2.6	2.6

TABLE 2 **Glazing characteristics of the Low-E coated IGU equipped with various CLC window films.**
The SHGC for the thermochromic window glazing system is given at various temperatures (10, 12, and 20 °C).
The visible light transmission remains constant at various temperatures.

glazing type	Double clear	+ CLC narrow	+ CLC broad	+ CLC full broad	+ thermochromic
Tvis (%)	84	81	81	79	79
SHGC	0.70	0.64	0.59	0.46	0.65 > 0.63 > 0.46
U-value (W/(m2K))	1.1	1.1	1.1	1.1	1.1

2.3 DESIGNBUILDER SIMULATIONS

The building's energy performance was simulated using the software DesignBuilder. A model office was designed having side offices (3.6 x 5.4 x 2.7 m) with one outdoor facing window and corner offices (5.4 x 5.4 x 2.7 m) with two outdoor facing windows. The four identical sides of the office are oriented towards the North, East, South and West (Figure 5). The window-to-wall ratio of the model office was 60%. The floor and ceiling of the office were designed to be adiabatic, to mimic an office space with adjacent building levels. The outdoor walls are medium weight walls having a U-value of 0.25 W/(m^2K). The building is equipped with an LED lighting system having a normalised power density of 2.5 W/m^2 per 100 lux and is turned on when the illuminance level drops below 400 lux at a working height of 0.8 m during occupied hours. The HVAC system is based on the 'Best practice' template defined in DesignBuilder. The heating system runs on natural gas and has a coefficient of performance (CoP) of 1.0 and is activated when the indoor temperature of a room drops below 20 °C. For operation schedule the DesignBuilder template 'Office_OpenOff_Heat' is used. The cooling system runs on electricity from the grid and has a CoP of 2.5 and is activated when the indoor temperature rises above 25.5 °C during occupied hours (DesignBuilder template 'Office_OpenOff_Cool'). The mechanical ventilation is turned on when the air rate drops below the minimum requirement of 10 l/s per person and follows the 'Open_OpenOff_Occ' schedule defined in DesignBuilder. Natural ventilation is turned off. Furthermore, the activity is based on the 'Generic Office Area' template defined in DesignBuilder. The model office has an occupation density of 0.111 people/m^2 and operates according to the standard open office occupancy schedule (DesignBuilder template 'Office_OpenOff_Occ'). During the operational hours defined by this occupancy schedule office equipment is used with a power density of 11.77 W/m^2.

During the simulations, all modelling parameters are kept constant. Only the glazing system is varied according to the characteristics described in the previous section. The building's energy use for lighting, heating, and cooling is gathered for the building equipped with various glazing designs. For the thermochromic glazing, DesignBuilder varies the glazing characteristics according to the outdoor temperature. In this case, the glazing characteristics are defined at 10, 12, and 20 °C. At the average between two defined switching temperatures DesignBuilder switches to the corresponding glazing characteristics. This means that <11 °C the glazing characteristics as set for 10 °C are used, at outdoor temperatures between 11 and 16 °C the glazing characteristics as set for 12 °C are used, and at outdoor temperatures >16 °C those as set for 20 °C are used. The energy use calculations were done for the climates of Guangzhou and Lisbon, which have warm and sunny conditions throughout almost the entire year, and for Amsterdam and Beijing, which have variable seasons with fluctuating temperatures. The weather data files are downloaded from www.climate.onebuilding.org, which provided Typical Meteorological Year (TMY) datasets for the specific locations, which were then imported into the DesignBuilder model.

3 RESULTS

3.1 ENERGY SAVING POTENTIAL OF CLC WINDOW FILMS ON DOUBLE GLAZING

The energy consumption of the model building equipped with double glazing and various CLC-based window films was calculated for the climates of Guangzhou, Lisbon, Amsterdam, and Beijing. The energy use for lighting, heating, and cooling was included and the total energy consumptions are compared to each other (Figure 6A). These simulations show that in climates with warm temperatures all year through (e.g. Guangzhou and Lisbon) almost no energy use for space heating is required to maintain a comfortable indoor temperature and the building's energy consumption is mainly due to space cooling. When applying static CLC-based window films to the glazing, an increasing amount of energy can be saved with decreasing SHGC. This translates to an energy saving of up to 24 and 26% in Guangzhou and Lisbon, respectively, when applying the CLC full broadband film to the glazing (Figure 6B). In these climates there is no additional benefit of applying a thermochromic window film, as rejection of solar heat is beneficial almost all year through.

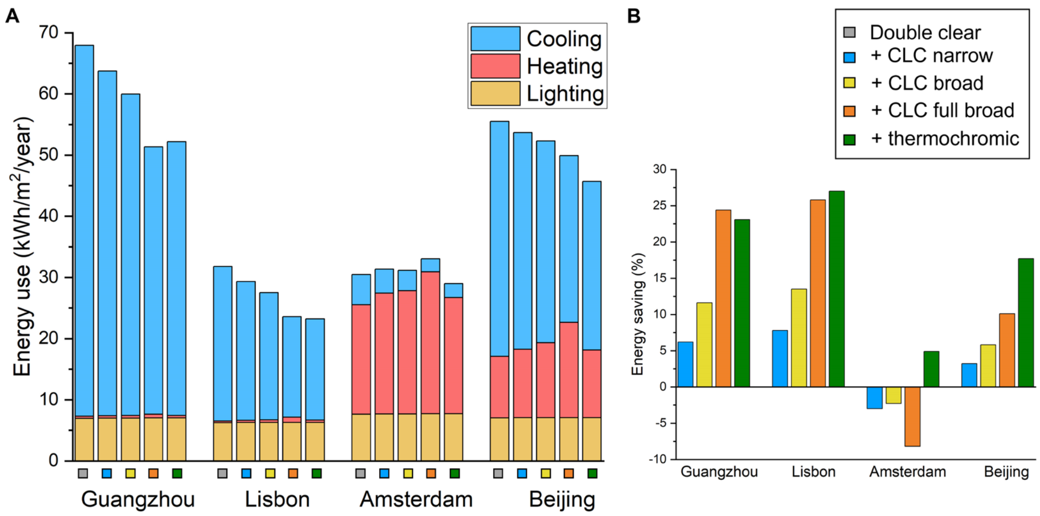

FIG. 6 (A) Annual energy use for lighting, heating, and cooling of the simulated building equipped with double glazing and various CLC window films in various climates. The legend in panel (B) also corresponds with the squares below the bars, which indicate the implemented glazing type. (B) Energy saving percentage of the simulated building compared to double glazing.

This outcome changes when performing the simulation in climates in which outdoor temperature conditions fluctuate more heavily between seasons (e.g. Amsterdam and Beijing). In these climates the energy use for space heating makes up a significant portion of the building's annual energy consumption and can even become the main source of energy consumption, such as in Amsterdam. The simulations reveal that applying a static CLC-based window film to the double glazing of the model building decreases the energy use for space cooling. However, the energy use for space heating increases. This effect is caused by the additional energy use required for space heating in winter (Figure 7). As solar heat is also rejected on colder days (e.g. winter) it takes more energy for the heating system to remain a comfortable indoor temperature. In Beijing, where cooling energy use is still the main source of the building's energy consumption, the energy savings on cooling are still larger than the additional required energy use for space heating, and an overall annual energy saving of 10% is achieved. In Amsterdam, where heating is the main source of the building's energy consumption, the additional required energy use for space heating when applying a static CLC-based window film is larger than the energy savings on space cooling, which results in an increase of the annual energy use. To prevent the additional required energy use for space heating in climates like Amsterdam and Beijing, a thermochromic window film can be applied to the glazing of the model building. When doing so, solar heat is rejected on warm days, which saves energy use on cooling, whereas solar heat is allowed to enter the building on cold days, which prevents the additional required energy use for space heating (Figures 6 and 7). In this case, an overall annual energy saving of 5 and 18% can be achieved in Amsterdam and Beijing, respectively, compared to double glazing. When comparing the energy saving performance of the thermochromic film to that of a static CLC-based window film reaching the same SHGC (e.g. the CLC full broadband film), the thermochromic film improves the energy efficiency of the building, at 13% and 8% in Amsterdam and Beijing, respectively.

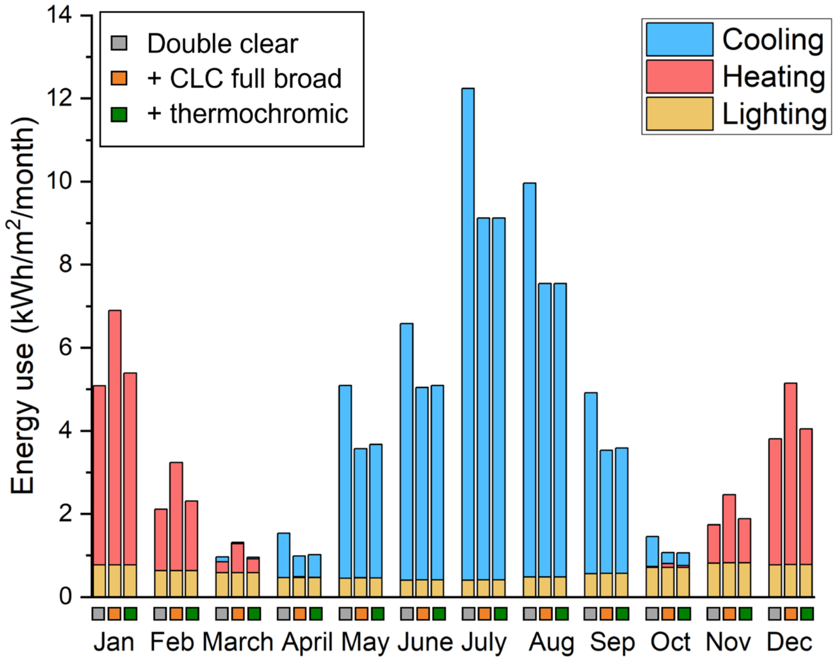

FIG. 7 Monthly energy use for lighting, heating, and cooling of the simulated building equipped with double glazing and a CLC full broadband or thermochromic window film in Beijing.

3.2 ENERGY SAVING POTENTIAL OF CLC WINDOW FILMS ON LOW-E COATED DOUBLE GLAZING

Similar simulations were carried out for a model building that is equipped with Low-E coated double glazing. Low-E coatings increase the insulating value of the glazing and thus lower the U-value.(Jelle et al., 2012; Rezaei et al., 2017) Therefore, the energy use for space heating on cold days (e.g. winter) decreases. Simultaneously, the energy use for space cooling on warm days (e.g. summer) increases, as indoor heat cannot leave the building as easily. In warm climates, such as Guangzhou and Lisbon, this effect causes an increase in overall annual energy consumption of the model building when compared to double glazing. In climates bearing distinct summer and winter seasons, such as Amsterdam and Beijing, replacing double glazing with Low-E coated double glazing does enhance the energy efficiency of a building.

When implementing the CLC-based window films to the Low-E coated glazing of the model building in Guangzhou and Lisbon, similar trends can be discovered as in the case of double glazing (Figure 8A). The energy use for space cooling decreases with decreasing SHGC. Overall annual energy savings of up to 25% and 29% can be reached when equipping the glazing with a CLC full broadband film (Figure 8B). Additionally, in the case of Low-E coated glazing there is no additional benefit of applying a thermochromic glazing in these climates.

With the model building being equipped with a Low-E coated double glazing, the energy use for space heating decreases to a large extent. Therefore, space cooling becomes the major source of energy consumption both in the climates of Amsterdam and Beijing. When applying static CLC-based window films to the glazing of the model building, the energy savings on cooling on warm days (e.g. summer) remains larger than the additional required energy use for space heating on cold days (e.g. winter, Figure 8). This results in an overall annual energy saving up to 12% and 19% for Amsterdam and Beijing, respectively, when using the CLC full broadband film. In the case where a thermochromic CLC-based window film is used, the energy savings could even increase further to 18% and 22%, respectively.

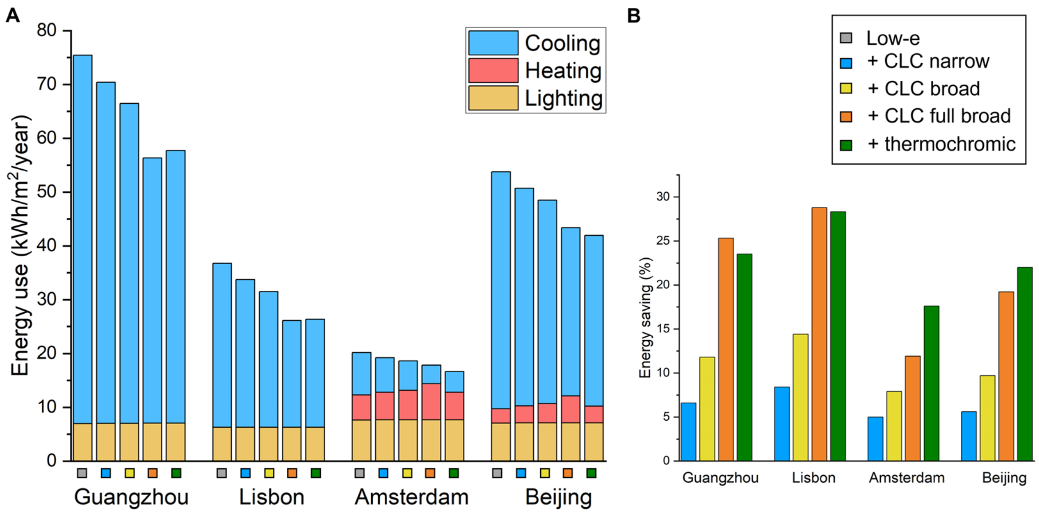

FIG. 8 (A) Annual energy use for lighting, heating, and cooling of the simulated building equipped with Low-E coated double glazing and various CLC window films in various climates. The legend in panel (B) also corresponds with the squares below the bars, which indicate the implemented glazing type. (B) Energy saving percentage of the simulated building compared to Low-E coated double glazing.

4 CONCLUSIONS

When renovating our model office with static CLC-based window films an annual energy saving between 24% and 29% can be achieved in warm climates, such as Guangzhou and Lisbon by reducing the cooling load. In climates with distinct summer and winter seasons, the energy saving increases when decreasing the SHGC of the film. In climates with fluctuating weather conditions throughout the year, such as Amsterdam and Beijing, the application of static CLC-based window films also reduces the cooling load of our model office, but simultaneously increases the heating demand during cold periods. Therefore, the annual energy savings are smaller compared to that in warm climates, especially when combined with double glazed buildings, in which heating contributes a large portion of a building's energy use. In these climates, one would benefit from the renovation of buildings using thermochromic CLC-based window films; a thermochromic film can improve the annual energy saving between 3% and 13% compared to a renovation with a static CLC-based window film. An annual energy saving between 5% and 22% can be achieved when renovating our model office with a thermochromic CLC-based window film.

The simulation results also show that the energy performance of a building in warm climates, such as Guangzhou and Lisbon, does benefit from a Low-E coating compared to clear double glazing. In these climates, renovations that add solar heat rejection to currently installed double glazing, such as with the addition of CLC-based window films, are preferred over improving the glazing's U-value. However, in climates with distinct summers and winters, such as Amsterdam and Beijing, Low-E coated double glazing has an energy efficiency benefit over clear double glazing. Here, combining good insulating properties with adaptive solar heat rejection results in the best energy performance.

For these climates, renovations are thus recommended in which clear (single or double) glazing is replaced by Low-E coated double glazing with adaptive solar heat control. These findings are in line with earlier reported building simulations, which report an energy saving between 15 and 30% of thermochromic glazing in combination with a Low-E coating compared to clear double glazing in the climate of The Netherlands (Mann et al. 2020, 2021).

Although glazing plays a significant role in the energy efficiency of buildings, the renovation of buildings has to be an integral solution that also includes other elements, such as the opaque elements of buildings, the efficiency of HVAC installations, and the thermal and daylight comfort of occupants. The introduction of other building materials for the walls and roofs (with different insulation values), as well as the introduction of screens and blinds to improve daylight comfort, are likely to influence the outcome of the energy performance simulations and thus the impact of the CLC-based window films studied in this work. Therefore, we advise conducting further studies to understand the interplay between various building use cases and the proposed window films.

Nevertheless, based on the findings presented in this work, optical window films based on CLC materials have real potential as an energy-saving renovation solution. To optimize the energy saving potential for various climates around the world, it is recommended to drive the material development of CLC-based window films towards both static as well as thermochromic solar heat rejection films. To be competitive in performance and energy saving to current window film products on the market, it is necessary to fabricate films with full broadband reflection properties and large optical contrast between cold and warm states, while maintaining the benefit of a highly visible light transmission. In addition, it should be ensured that the films are fabricated in a cost-effective way and at high throughput, such as via roll-to-roll fabrication methods.

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