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SMART WINDOWS WITH DYNAMIC SPECTRAL SELECTIVITY – A SCOPING STUDY

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ABSTRACT

Windows with the ability to selectively and dynamically control the transmission of (i) visible light, (ii) near-infrared sunlight, and/or (iii) longwave infrared radiation generate promising opportunities for low-energy building operation with high indoor environmental quality. This paper presents a simulation-based scoping study that analyzes the performance of switchable glazing with different spectral properties in four climates, for three orientations and three window sizes. Integrated daylight and thermal predictions with dynamic fenestration properties were carried out in a co-simulation approach that couples the Radiance three-phase method to ESP-r. Results are used to map the various smart window types to their most promising application area.

INTRODUCTION

Careful selection of the properties and dimensions of windows is essential for optimizing the indoor environmental quality and energy performance of buildings. Nowadays, special functional layers, such as solar control films and low-emissivity coatings, are regularly applied for mitigating the impact of solar heat gains and for higher thermal resistance (Jelle et al. 2012; IEA 2013; US DOE 2014). Although these technologies have substantially improved the performance of fenestration systems, they also have some shortcomings. One of such limitations is that the properties of glazing systems are fixed over time, and that they can therefore not respond to, or take advantage of, the variability in climatic conditions (Loonen et al. 2013). A solar control film, for example, will typically help reduce cooling loads in summer, but does this at the cost of view to outside and also blocks useful solar gains in periods when no cooling is needed (Khandelwal et al. 2014). As a result, compromises in the design phase are often needed to achieve satisfactory performance given multiple criteria under a wide range of operating conditions (Ochoa et al. 2012; Ghisi and Tinker 2005; Peippo, Lund, and Vartiainen 1999).

Breakthroughs in materials science are now starting to open up a range of new possibilities by allowing building designers to influence window-related trade-offs in a more dynamic way. Recently, materials with switchable reflection/transmission properties in three different parts of the electromagnetic spectrum have been reported in literature (Baetens, Jelle, and Gustavsen 2010) (Figure 1).

1. The most widely-known type comprises smart windows based on e.g. electrochromic principles or liquid crystal coatings, which have the ability to modulate solar gains and daylight levels by absorbing a variable amount of incident solar radiation (Granqvist et al. 2009; Loonen et al. 2014). A number of fenestration products of this type are already commercially available. Such window technologies operate primarily in the visible part of the solar spectrum. They can therefore simultaneously influence indoor thermal and visual conditions.
2. An alternative, and more novel switchable glazing technology focuses on modulating reflection / transmission properties in the non-visible, near-infrared (NIR) part of the solar spectrum (Llordés et al. 2013; Lu et al. 2015; Khandelwal et al. 2015). The interest in this type of switchable window coatings is explained by the fact that approximately 50% of the energy of sunlight is contained in this NIR range ($700 > \lambda > 2000$ nm) (Figure 1) and that altering these properties does not interfere with daylight or reduced views (Ye, Meng, and Xu 2012). A recent simulation study for US climate conditions demonstrated that, by controlling these NIR solar heat gains, a reduction in primary energy consumption for heating and cooling in the range of 3 to 9% can be achieved (DeForest et al. 2015).
3. Interacting with the exchange of longwave radiation is a third way of influencing the radiant energy balance of windows. Nowadays, the application of low-emissivity (low-e) coatings is very common and considered as an effective approach for improving the thermal performance of windows, especially in heating dominated climates (Jelle, Kalnæs, and Gao 2015). However, in certain periods of the year, low-e coatings also have a negative effect. For example, it restricts the ability of buildings to release heat to the ambient environment during summer nights, and thereby contributes to higher energy demand for cooling. Coatings with switchable emissivity

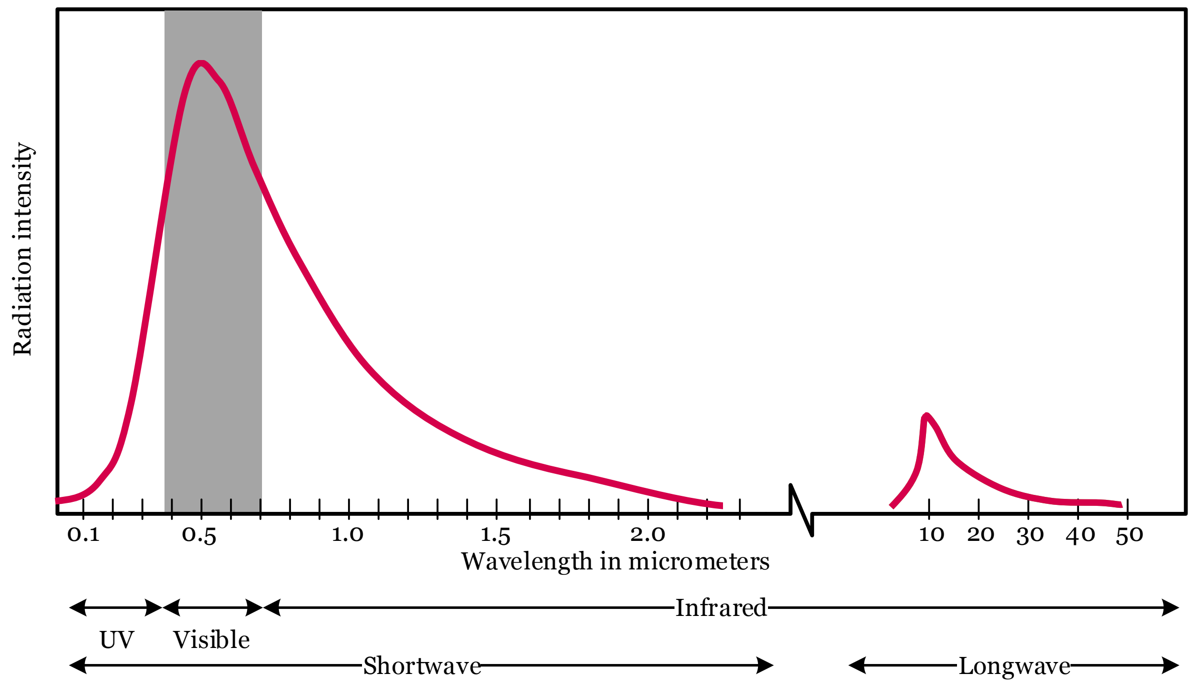

Figure 1. Illustration comparing the intensity of solar and terrestrial radiation. Because of the sun's high surface temperature, most of its energy is radiated at wavelengths shorter than 4 µm, with the greatest concentration in the visible range of the electromagnetic spectrum.

properties in the wavelength range of 10 to 30 µm are still in an early phase of development (Wang et al. 2015; Wu et al. 2013), but have a promising potential for further reducing the energy and CO_2 footprint of buildings.

So far, most research on switchable windows has focused on the level of materials, devices and prototypes. In addition, a growth in the use of simulation-based analysis to support R&D activities can be observed for individual window technologies (Loonen et al. 2014). There is, however, still a lack of guidance on how such innovative glazing technologies could be integrated in buildings in a way that maximizes their performance. This type of information would not only be useful for building designers, but could also support materials scientists to decide on the most pertinent research and development activities (Bastiaansen et al. 2013; Lee et al. 2013; Hensen et al. 2015).

The objective of this paper is to contribute to the knowledge on the application of windows with dynamic spectral selectivity by means of a simulation-based scoping study. In this scoping study, the focus is on energy-saving potential for heating, cooling and lighting, and visual comfort. We rapidly scan and analyze the performance of various switchable glazing types for a range of different conditions, in terms of facade orientations, window sizes and climates.

METHODODOLOGY: SCOPING STUDY

The methodology for the scoping study that is presented in this paper is described in five steps: (i) baseline model, (ii) window properties, (iii) performance indicators, (iv) simulation scenarios, and (v) window control strategies.

Baseline model

The baseline simulation model is a single-zone office space (3.6*5.4*2.7 m) with a window-to-wall ratio of 60%. The perimeter façade is modelled as an external wall while all other surfaces face similar office spaces. All opaque construction elements in this reference model have medium thermal mass. The external wall has a thermal resistance (R-value) equal to 3.5 m^2K/W

The perimeter office zone is occupied by two people who are present on weekdays from 8-18 h. Each occupant represents an internal heat gain of 120 W. Internal gains from electronic equipment (laptop, printer, etc.) correspond to 50 W/person, operating only during occupied hours. Artificial lights are controlled by a sensor inside the zone, 1.5m from the façade at work plane level. The lights with a nominal lighting power density of 12 W/m^2 are continuously dimmed to meet the set point of 500 lux.

The heating, ventilation and air conditioning (HVAC) system is modeled as an ideal convective system, because the main interest of this work is on daylight control and management of solar gains. The HVAC system has a heating set point 21ºC starting one hour before the beginning of the occupied hours until the zone is empty again (7-18 h.) and 14ºC during the rest of unoccupied hours. The cooling set point is set to 25ºC occupied and 30ºC for unoccupied hours. Ventilation with heat recovery (90% efficiency) is set to 3 air changes per hour (ACH) during occupied hours and 0.2 ACH during unoccupied hours, while infiltration was assumed to have a constant value of 0.3 ACH throughout the year.

Window properties

Windows with three different types of switchable glazing properties are analyzed in this study. All switchable windows share one common reference state, having the properties of a regular low-emissivity double glazed window.

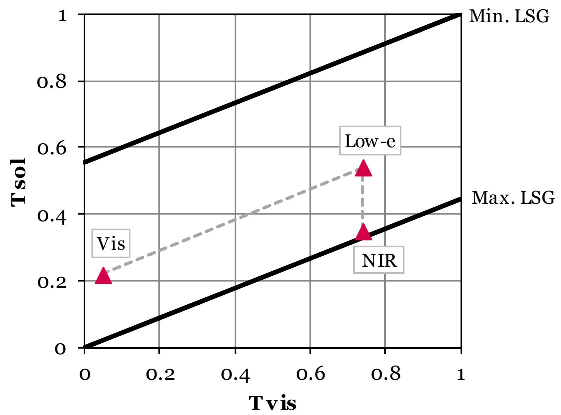

Figure 2. Relationship between visible transmittance and solar transmittance. Note that windows with values below the max. LSG line and above the min. LSG line are physically impossible.

Figure 2 shows how the properties of the windows with low visible transmittance and high NIR reflectance relate to this reference situation (low-e). The switchable window state with high NIR reflection has a very high light-to-solar heat gain (LSG) ratio. In this case, it means that all solar energy in the wavelength range λ > 700 nm is reflected, without affecting the transmittance of visible light. For the case with low visible transmittance, we assumed that the absorption of sunlight is equally spread over the entire solar spectrum. This case therefore results in the situation that switching of window properties happens between two points with equal LSG value. The end point of VLT = 0.05 is selected because it is generally considered that values as low as this lead to a moderate risk for glare discomfort (Lee et al. 2013; Piccolo and Simone 2009)

The third type of adaptability, the changing of properties in the longwave radiation range is achieved by varying the emissivity of the inside surface of the outside glazing pane from 0.05 to 0.84. The algorithms in LBNL Window6.3 indicate that doing this would lead to an increase in window U-value from 1.6 W/m^{2}K to 2.7 W/m^{2}K.

A summary of all relevant properties of the different switchable glazing systems is presented in Table 1.

Table 1. Overview of switchable glazing properties in the (i) visible, (ii) near-infrared and (iii) longwave part of the solar spectrum. The arrows indicate low (↓) or high (↑) values of visible light transmittance (VLT), solar transmittance (Tsol) and emissivity (ε), respectively.

		VLT [-]	Tsol [-]	ε [-]	U-value [W/m^{2}K]
Visible	↓	0.05	0.22	0.05	1.6
	↑	0.74	0.54	0.05	1.6
NIR	↓	0.74	0.35	0.05	1.6
	↑	0.74	0.54	0.05	1.6
Longwave	↑	0.74	0.54	0.84	2.7
	↓	0.74	0.54	0.05	1.6

Performance indicators

Two aspects are considered in the switchable window performance assessment: energy and comfort.

To evaluate energy performance, we compute the total primary energy use intensity (EUI) in kWh/m^2 for heating, cooling and lighting. Throughout the case studies, we assume that the seasonal heating efficiency = 0.9, cooling COP = 3, and the primary energy conversion factor for electricity = 2.56, according to (NEN7120 2011).

Facade-related visual comfort is influenced by a number of factors with complex interactions (Reinhart and Wienold 2011). The ambition is to use the switchable windows to contribute to well-distributed daylight illuminance in the absence of discomfort glare. This is evaluated with two indicators:

— **Useful daylight illuminance (UDI).** Daylight utilization is assessed by computing the percentage of occupied hours that daylight illuminance on the work plane falls within certain bounds. Four different categories according to the classification of (Mardaljevic et al. 2012) are considered: fell short (<100 lux), supplementary (100-300 lux), autonomous (300-3000 lux) and exceeded (>3000 lux).

— **Daylight glare probability (DGP).** Discomfort glare is assessed using DGP, as it was shown to be the most robust glare metric in a comparative study under a wide range of ambient conditions (Jakubiec and Reinhart 2011). In this study, a conservative glare scenario is considered in which the occupants' view direction is always facing the façade. Three different categories for discomfort glare are distinguished, according to the classification in (Reinhart and Wienold 2011), where the risk is (i) intolerable (DGP > 0.45), (ii) disturbing (0.35 < DGP < 0.45), or (iii) not disturbing (DGP < 0.35).

Simulation scenarios

Various integrated daylight and thermal simulations are conducted to assess the performance of the switchable window types. We defined one baseline simulation scenario, and consider variations in terms of climate, façade orientation and window-to-wall ratio. Table 2 gives an overview of the different scenarios that are investigated in this study; items in bold represent the baseline scenario.

Table 2. Overview of variants in the parametric study.

Climate	Stockholm, **Amsterdam**, Berlin, Madrid
Orientation	East, **South**, West
WWR	30%, **60%**, 90%

The four climate were selected because together they cover a wide range of climates representative for the European continent. Table 3 presents an overview of heating and cooling degree days for each of the four cities as an indication of the range of climate conditions that is covered in this study.

Table 3. Overview of heating degree days (HDD) and cooling degree days (CDD) for the four climates.

	HDD	CDD
Stockholm	4286	49
Amsterdam	3038	65
Berlin	3317	147
Madrid	2023	612

Window control strategies

The definition of an appropriate window control strategy is of essential importance for analyzing the performance of switchable glazing technologies (Jonsson and Roos 2010). Table 4 summarizes the control strategies that were considered in this study.

Table 4. Window control strategies

	Switch to other state if
VLT	Incident solar radiation > 250 W/m^2
NIR	Incident solar radiation > 250 W/m^2
Longwave	Ambient temperature < indoor temperature AND building is not in heating mode

MODELING AND SIMULATION

Simulation strategy

This study uses a coupled simulation approach to analyze the interactions between daylight performance and energy efficiency. Annual dynamic daylight simulations for the different window states are carried out using the Radiance three-phase method. This method is a validated, new addition to the Radiance suite of daylight simulation tools (Ward and Shakespeare 1998), which was specifically developed to enable high-resolution annual daylight performance predictions at reduced computational cost (Saxena et al. 2010; McNeil and Lee 2013). The daylight predictions are performed in a pre-processing phase.

Building energy simulations (BES) are carried out using ESP-r (Clarke 2001). Unlike most other whole-building simulation tools, ESP-r offers relatively high flexibility for performance prediction of adaptive building shell components such as switchable windows (Loonen, Hoes, and Hensen 2014). The changes in window properties are assigned during simulation run-time. This is achieved by making use of the connection between ESP-r and the Building Controls Virtual Test Bed (BCVTB) (Wetter 2011; Hoes et al. 2012). The control strategy is directly implemented in the BCVTB using actors from its Ptolemy II library. This coupling strategy also takes care of assigning the correct internal heat gains for lighting, depending on daylight illuminance corresponding to the values that were computed in the pre-processing phase.

RESULTS

Daylight performance

Figure 3 compares the simulation results in terms of UDI for the regular window and the case with switchable VLT. The difference is most notable for the number of occupied hours that the illuminance of 3000 lux gets exceeded.

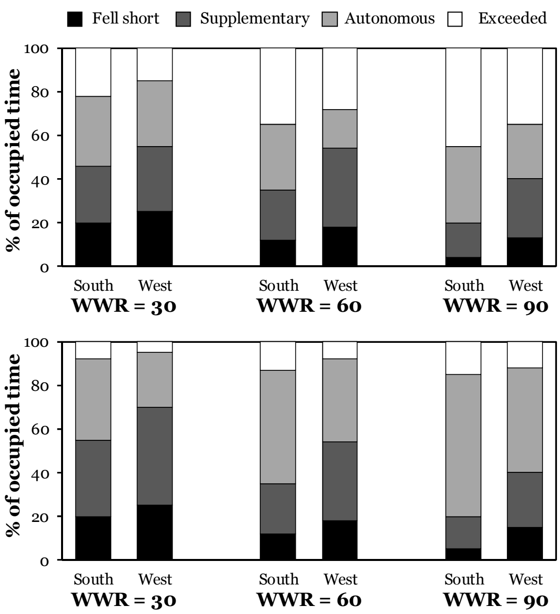

Figure 3. Useful daylight illuminance results for the regular window (top) and switchable VLT window (bottom). Results are shown for two façade orientations and three window-to-wall ratios.

The extent of possible discomfort due to the too high daylight illuminance levels gets significantly reduced in the case of controlled light transmittance, most notably for the South façade.

During the hours with relatively low daylight illuminance, the difference between the two cases is relatively low. This effect can be explained by the fact that during most of these hours, the switchable glazing system is switched in the transparent mode, and hence leads to similar lighting conditions as the regular façade.

The results for glare discomfort are presented in Table 5, showing again the comparison between switchable and non-switchable visible light transmittance. The difference in results for DGP is even more pronounced than the results for UDI. The amount of discomfort hours shows a substantial reduction when the window transparency is reduced to 5% during times with high incident solar radiation.

Table 5. Daylight Glare probability classification for the regular window (top) and switchable VLT window (bottom). Results are shown for two façade orientations and three window-to-wall ratios.

Orientation	WWR	DGP Disturbing [h]	DGP Intolerable [h]
Regular			
South	30	98	112
	60	114	198
	90	182	325
West	30	179	256
	60	172	378
	90	212	421
Switchable VLT			
South	30	31	4
	60	52	9
	90	56	23
West	30	22	12
	60	44	21
	90	51	56

Energy performance

Figure 4 shows a comparison of the primary energy demand for different WWR values (South façade, Amsterdam). The results show that for windows with switchable non-visible properties (NIR and longwave), the results are highly sensitive to the window area. Especially larger windows lead to a large increase in energy consumption. On the other hand, switching in the visible part of the spectrum leads to much less difference in the results. This finding indicates the possibility of designing buildings with large glazed facades, without having a significant penalty in terms of increased energy consumption.

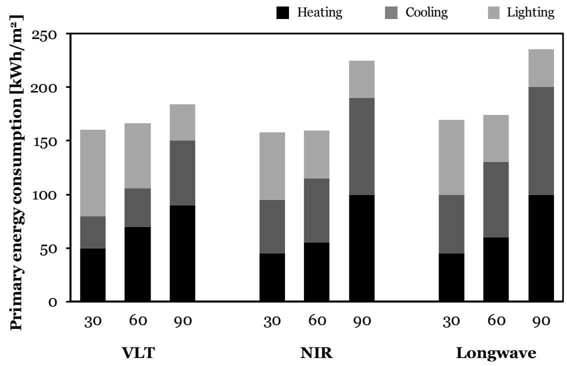

Figure 4. Energy performance of the three switchable window types for a façade with South orientation in Amsterdam. Results are shown for window-to-wall ratios of 30, 60 and 90%.

In Figure 5, the results for the four different climates are presented. These results show that lighting energy consumption has a quite large influence on the overall energy consumption. The windows that switch in the non-visible part of the spectrum need considerably less energy for lighting. However, these cases also show a higher energy demand for cooling. The lowest cooling energy demand is observed in the situation with visible switching. Compared to longwave switching, the dynamic NIR reflectivity also reduces cooling energy demand, but not as effective as the case with VLT control. These results correspond with the values for solar transmittance, as presented in Table 1. However, these static material properties are not sufficient to characterize the performance of switchable glazing systems, because (i) they do not account for the dynamic effects that occur at different control strategies, (ii) do not take the total building energy balance in consideration, and (iii) do not distinguish whether most of the incident radiation is absorbed (VLT case) or whether it is reflected (NIR case). The complex balance betwwen heating, cooling and lighting energy use in Figure 5 clearly indicates the need to develop and select switchable glazing technologies in response to the needs of local climatic conditions. For example, a switchable VLT window offers the lowest total energy demand for Madrid, but such a window would not be recommended for energy-saving purposes in Stockholm.

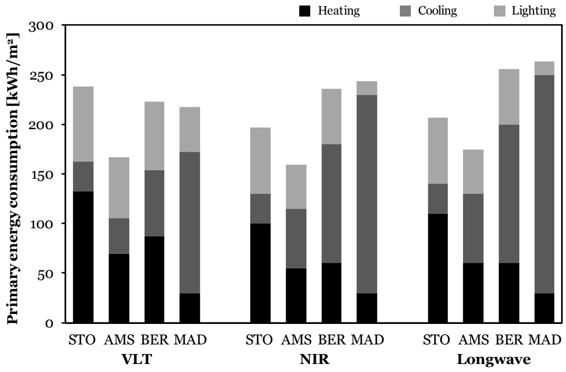

Figure 5. Energy performance of the three switchable window types for a façade with South orientation and 60% window-to-wall ratio. Results are shown for the climates of Stockholm, Amsterdam, Berlin and Madrid.

Finally, Figure 6 shows the energy performance results as a function of façade orientation. Although these results are useful to obtain a better global understanding of the performance of switchable glazing types, they do not lead to remarkable new insights. For all three window types, the lowest energy consumption is achieved for the South façade. In all three cases, the East façade has the highest heating energy consumption. In the situation where the admittance of solar gains is reduced (VLT and NIR), the heating load on the East façade is extra high because the contribution of passive solar gains to room heating gets reduced when the room is heating up in the morning hours. The consequences of this orientation effect are also visible for the West façade. By the time that high intensity solar radiation reaches the West façade, the office room is already warmed up. Because the longwave case has no ability to control the amount of solar gains, we can see there a much larger increase in cooling energy demand, compared to the other two cases (VLT and NIR).

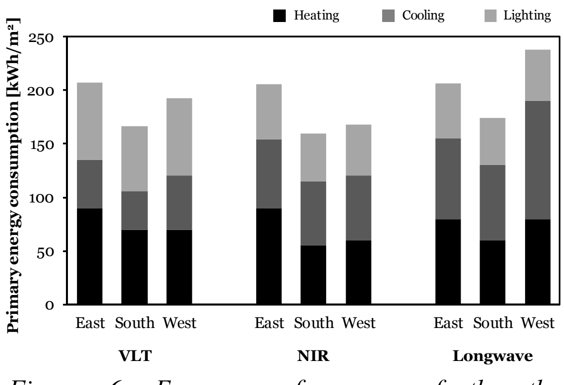

Figure 6. Energy performance of the three switchable window types for a façade with 60% window-to-wall ratio in Amsterdam. Results are shown for three orientations, East, South and West.

DISCUSSION AND CONCLUSION

The "Holy Grail of the fenestration industry" has been described by Selkowitz et al., (2003) as a window that can deliver *dynamic, responsive control of solar gain and glare, but permitting daylight use*.

This study has used a high-resolution modeling approach to evaluate how three advanced switchable window types, active in three different parts of the electromagnetic spectrum, are able to meet this long-term vision for well-controlled daylight and solar gains in buildings.

The results we showed are in line with the outcomes of various simulation studies that present an in-depth analysis of the individual switchable window types (Tavares et al. 2014; DeForest et al. 2015; Fernandes, Lee, and Ward 2013; Loonen et al. 2014). The distinguishing characteristic of this article is that it allows for a rapid side-by-side comparison of the relative performance of several technologies, because their evaluation was subject to the same simulation scenarios and boundary conditions.

Overall, the following main conclusions can be derived from this article.

- The concept of one-size-fits-all does not apply to switchable window technology. To achieve good performance, product developers and building designers should adapt the properties of switchable glazing technologies to the needs of individual situations.
- Dynamic transmittance of sunlight in the visible wavelength range not only influences solar heat gains, but also has a positive effect on visual comfort conditions and lighting energy use. Among the three tested glazing types, glazing systems that are active in this part of the spectrum have the highest energy-saving potential. It is essential to use coupled daylighting and thermal simulations to gain insights into such effects.
- Solar shading systems, such as blinds and screens or window coatings with controllable VLT transmission are needed to ensure acceptable visual comfort conditions, especially in cases with large window areas. It is not always fair to compare the energy performance of windows with and without shading system, because they do not lead to equivalent indoor conditions (Ochoa et al. 2012).
- The performance of switchable windows is very climate-dependent. Windows with switchable NIR reflection are most effective in climates which have both a considerable heating and cooling energy demand, whereas the ability to switch VLT is most effective/promising in sunny climates.
- Compared to the other two technologies, the performance potential of adaptive low-emissivity coatings is relatively low. Its effect appears to be almost insensitive to the façade orientation.

Three important limitations of this study should also be mentioned:

- We did not investigate the potential co-benefits of having switchable properties in multiple parts of the solar spectrum. It is expected, however, that independent control of transmitted visible and non-visible solar energy can lead to extra advantages for low-energy building operation with high indoor environmental quality.
- This study only assessed two states per switchable window type, at the end points of the dynamic range. It would be interesting to analyze if adding the option for switching to intermediate states would lead to different conclusions.
- Although it is known that the chosen window control strategy can have a significant influence on the performance of switchable glazing, we only examined a limited number of options. Future work should investigate more control options, including the possibility for optimization-based control strategies.

ACRONYMS

ACH	Air changes per hour
AMS	Amsterdam
BCVTB	Building controls virtual test bed
BER	Berlin
BES	Building energy simulation
CDD	Cooling degree days
COP	Coefficient of performance
DGP	Daylight glare probability
EUI	Energy use intensity
HDD	Heating degree days
HVAC	Heating, ventilation and air-conditioning
LSG	Light-to-solar heat gain ratio
MAD	Madrid
NIR	Near infrared
STO	Stockholm
Tsol	Solar transmittance
Tvis	Visible light transmittance
UDI	Useful daylight illuminance
VLT	Visible light transmittance
WWR	Window-to-wall ratio

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