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# Energy performance of novel low-cost inkjet-printed electrochromic glazing

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**SUMMARY**
Rising temperatures are leading to an increase in the cooling demand of buildings. Electrochromic (EC) glazing can be a promising solution for controlling solar heat gains while maintaining outdoor views. This paper presents the results of the monitoring of prototype panels of a novel type of inkjet-printed EC glass under real use and weather conditions in a small office building in the Netherlands. This building contained two identical west-facing meeting rooms of which one was equipped with EC triple glass IGUs and the other with normal triple glass IGUs. Each room was equipped with local heating/cooling units of which the energy use was monitored, and with an extensive environmental sensor network. Sensor and calendar data was fed into an energy balance model for each of the rooms for the entire measurement period, allowing to correct for differences between the two rooms with respect to heat losses and gains and use conditions. The results of the monitoring showed that in the meeting room with EC glass IGUs, the heating demand increased by 34% in Jan.-Mar. 2024 while in Sept. 2023 the cooling demand decreased by 3%. The main reason for the increase in heating demand was found to be the lower g-value of the EC glass IGUs in clear state as compared to the normal IGUs. The almost similar cooling demand was a result of a trade-off between the lower direct solar transmittance of the EC glass IGUs and the heating up of the absorptive layer inside the IGUs. Furthermore, an experiment with participants showed that in general in dark state, satisfaction with view clarity, daylight colour and daylight availability was higher for the EC glass IGUs. In transparent state, no significant difference was perceived between the EC glass IGUs and standard IGUs, except for view clarity.

*Keywords: Electrochromic glazing, energy performance, monitoring.*

## 1. INTRODUCTION

Rising temperatures are leading to an increase in the cooling demand and overheating risk of buildings. Dynamic switchable glazing, like Electrochromic (EC) glazing, can be a promising solution for controlling solar heat gains and daylight admittance while maintaining access to outdoor views. By applying a small electric potential, the transparency of the glass can be adjusted to modify the visible light and direct solar transmittance. It can be switched over a range between a clear state with high transmittance, and a tinted state with low transmittance. To produce EC glass, a thin-film EC coating is placed on a glass panel. The coating consists of several layers: at the centre, an ion-conducting electrolyte sandwiched between an active EC layer at one side and a passive counter-electrode layer at the other side. Transparent conductors form the outermost layers (Lee et al., 2006). The thin film deposition can be based on several methods. The selected method affects the production costs and the durability of the end product (Kelly Waskett, 2016). The current high costs hinder the widespread application in buildings. Recently, a cost-effective type of EC glass using inkjet-printing was developed. Its effect on the cooling and heating demand and how it holds under real use and weather conditions is still uncertain.

Several earlier studies have investigated the performance of traditional EC glazing based on field test experiments or energy performance simulations. These studies examined possible energy savings based on different control regimes, environmental conditions or building types (Chambers et al., 2019; Piccolo & Simone, 2015; Papaefthimiou et al., 2006; Li et al., 2023; Klems, 2001); or compared the performance of EC glazing to other solar control devices (Fernandes et al., 2013; Kwee, 2020; Krarti, 2022). One study also included user satisfaction (Kelly Waskett, 2016).

The objectives of the present study, the Windows to the Future project, were: 1) to upscale the production facilities of inkjet-printed EC glazing, 2) to understand and overcome the key bottlenecks when integrating the technology into facades, 3) to understand to what extent the EC glass impacts the cooling and heating demand, as compared to regular high-performance triple glass for office spaces in temperate climates, 4) to explore the satisfaction of the technology by users, and 5) to understand to what extent the EC glass transmits daylight into the workplace and how the colouring of the daylight affects user perception. This paper will mostly address the objective 3 and includes some of the results related to objective 5. More results related to objectives 4 and 5 can be found in Luna-Navarro et al. (2024) and Chiucchiu et al. (2024). The EC glass used in this project was developed by Brite Solar.

## 2. MATERIALS AND METHODS

### 2.1. EC glass prototypes

The experiments were done in the OfficeLab at The Green Village on the TU Delft campus, the Netherlands. This building is equipped with HR+++ triple glass with a U-value of 0.6 W/(m$^2$K), a g-value of 0.48, and a light transmittance ($t_{vis}$) of 0.73. In the experimental room, the existing insulating glass units (IGUs) were replaced with IGUs with an EC layer. The thermal insulating properties of these IGUs were selected to correspond to the existing triple glazing. Furthermore, the thickness of the new IGUs matched the existing IGUs. The U-value of the EC glass IGU was measured to be 0.60±0.02 W/(m$^2$K); the light transmittance ($t_{vis}$) for the clear state between 0.40±0.05 and for the tinted state between 0.08±0.02; and the solar transmittance ($t_{sol}$) for the clear state 0.18 and for the tinted state 0.004. The software WINDOW was used to assess the g-value of the glass in clear and tinted state, which were respectively 0.35 and 0.34 (if the EC coating is placed on the innermost pane) or 0.26 and 0.04 (if the EC coating is placed on the outermost pane).

Due to the Covid-19 pandemic, the full-scale production line for the EC glass panes was inaccessible. As a result, the EC glass panes had to be produced by a lab printer with much smaller dimensions. The dimensions were therefore limited to 50 x 50 cm. As a consequence, the smaller EC glass panes (two sheets of 3 mm glass with in-between them the active layers) had to be laminated onto a 5 mm glass pane of the full window size (approx. 1 x 2.6 m). This ±11 mm thick glass laminate was used as one of the three glass panes of the IGU. The fixed windows in the façade were subdivided into 12 smaller panes while the operable window was subdivided into 10 panes (Figure 1). Even though the EC glass panes (by lamination) were integrated into a full size triple glass unit, sealing stripes were visible between the smaller EC panes. Table 1 provides the layering of the glass. It is important to mention here that the glass in the fixed windows had the EC glass laminate on the inside while in the operable window it was on the outside. The manufacturer recommended, as a precaution for this experimental version, to place the EC coating on the warm side of the glass to prevent a too low temperature of the coating in winter. However, as sun-shading, the coating should ideally be as close to the outdoor environment as possible.

**Table 1.** Layering of the triple glass IGUs.

| IGU configuration | Existing triple glass IGU | EC glass prototype fixed window | EC glass prototype operable window |
|---|---|---|---|
| Outer pane | 6 mm Stratobel laminated 33.1: 3 mm Planibel Clearlite / 0.38 mm PVB clear / 3 mm iplus 1.1. pos.2 | 5 mm iplus 1.1 (or equal) | 11 mm laminated EC glass |
| Cavity | 15 mm argon 90% | 13 mm argon | 13 mm air |
| Centre pane | 4 mm Planibel Clearlite | 5 mm iplus 1.1 (or equal) | 5 mm iplus 1.1 (or equal) |
| Cavity | 15 mm argon 90% | 13 mm air | 13 mm argon |
| Inner pane | 6 mm Stratobel laminated 33.1: 3 mm iplus 1.1. pos.2 / 0.38 mm PVB clear / 3 mm Planibel Clearlite | 11 mm laminated EC glass | 5 mm iplus 1.1 (or equal) |

**Figure 1.** West façade of the experimental room with EC triple glass IGUs (left) and of the control room with standard triple glass IGUs (right). In the operable window, six of the small panes faced material leakage issues resulting from the lamination process due to improper sealing and could not be used.

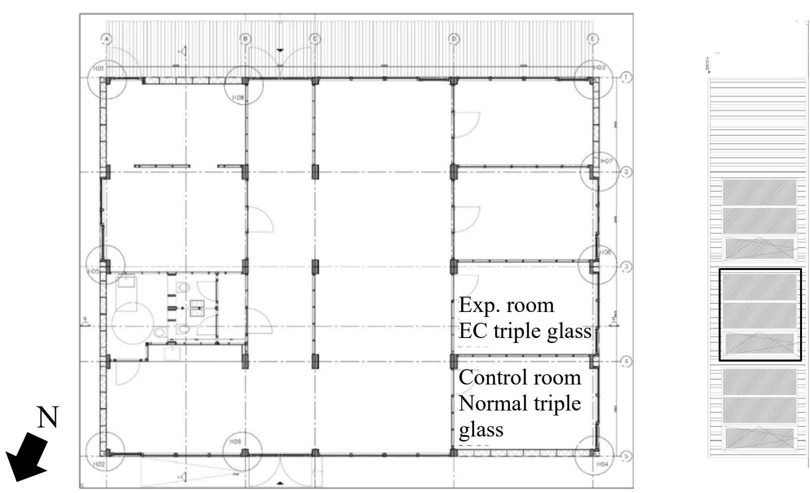



**Figure 2.** Floor plan and West façade of the OfficeLab. The windows highlighted contain the EC glass IGUs.

## 2.2. Test rooms set-up

The test building is a lightweight single-storey office building with a timber frame construction. Two similar meeting rooms, with a floor area of 17 m² each, at the western façade are part of the experimental setup: one control room where the original triple glazing is maintained and one experimental room where the original glazing is replaced with the prototype EC glazing (Figure 2). The two rooms have equal window areas with two fixed windows and one operable window.

## 2.3. Local heating and cooling units

To assess the heating and cooling demand, dedicated local heating / cooling units (portable air conditioner Whirlpool PACW212HP) were placed inside the two rooms and set to the same set-point temperatures (25ºC in cooling mode and 21ºC in heating mode, with a dead band of 1 ºC on both sides, from 3 am till 6 pm). Each unit was connected to a thermostat which was mounted on a wall. The electricity use of the heating / cooling units was measured with SXD10/5 0-10 ampere clip-on CTs attached to the electricity cable of each device and connected to an Eltek GD40A transmitter. The COP for heating was 2.8 and the EER for cooling 2.6.

## 2.4. Hourly heat balance corrections

The difference between the cumulative heating or cooling output of the local heating / cooling unit inside the two rooms provides an indication of the energy saving potential of the EC glass. However, differences between the two rooms (occupancy, ventilation rates, opening of doors and windows, electric lighting use, infiltration rate, and heat losses in general) will occur. To correct for these effects, a heat balance model was set up for each room for each hour of the full measurement period. This model was fed with data from environmental sensors, the outlook calendar of the rooms and the properties of all surrounding materials. It includes heat transmission through the floor, the roof, the opaque façade, the glass, and the partition walls; infiltration; heat transfer through mechanical ventilation; heat transfer through natural ventilation when the window was open (BLAST model); ventilative heat transfer to the main office when the door was open (stack model); internal heat gains from people, equipment, and lighting; solar heat gains through the glass. The energy use of the air-con unit in the two rooms was then compared and corrected for differences in the heat balance which were not a result of the glass, for every hour of the measurement period. This enabled us to correct for the different position of the rooms (corner versus centred) and differences in use. Also, pyranometers mounted behind the glass of each room ensured that the real solar gains were used in the analysis.

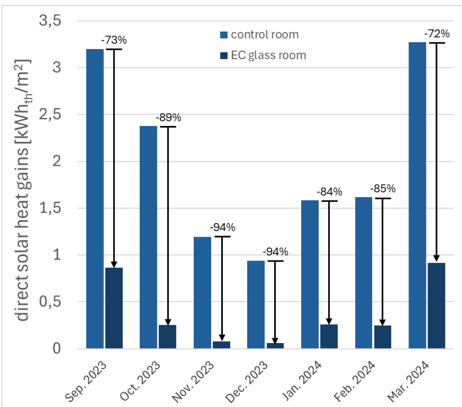
## 2.5. Sensors and data acquisition system

The meeting rooms and the offices next to them were equipped with multiple sensors to measure environmental variables. The actual monitoring campaign took place from Aug. 15, 2023 till March 31, 2024. Because the OfficeLab was undergoing construction works from April 2024 till Oct./Nov. 2024 the sensors had to be removed. Table 2 provides an overview of the installed sensors. All Eltek transmitters transmitted their data to an Eltek Squirrel RX250 receiver.

**Table 2.** Overview of installed sensors and transmitters.

| Measured property | Sensor | Transmitter | Position |
|---|---|---|---|
| Direct solar transmission through glass | Thies GSM 10.7 pyranometers | Eltek GenII GS-44 | behind the glass at 1.1 m above the floor (same height as outdoor one) |
| Outdoor solar radiation | Thies GSM 10.7 pyranometer | Eltek GenII GS-44 | in front of the façade, outdoors, at a height of 1.4 m above the ground |
| Outdoor weather | Vaisala WXT536D | Eltek TMET | in front of façade at 1.5 m height |
| Indoor temp. and RH | Eltek GC-10 T and RH sensors and transmitters | | at a height of around 1.5 m |
| Amount and temp. of mechanical air supply | E+E576 air flow sensors thermocouples type T | Eltek GS41AV and GS24 transmitters | inside the supply ducts |
| Window and door states (open/closed) | magnetic contact sensors | Eltek GenII GC60 transmitters | On openable windows and doors. The doors had automatic closers. |
| EC glass IGU surface temperature | thermocouples type T | GS24 transmitter | On indoor and outdoor glass surface at a height of approx. 1 m |
| EC glass IGU heat flux | Hukseflux HFP01 | GS44HD transmitter | Same as above |

The use of the electric lighting could not be monitored. Lighting use was estimated based on occupancy of the rooms (only then the lights were switched on in reality) and the installed power (65.6 W). The heat gains by equipment were considered small compared to the heat gains by people and lighting and were estimated from the number of people present, assuming 50% of the people brings a laptop with them. Since not everything could be monitored for practical reasons or because of privacy concerns, the following were estimated from the Outlook calendars of the meeting rooms: the time and duration of meetings in the meeting rooms and the number of people present; the time and duration when the flexible partition wall between the two meeting rooms was open.



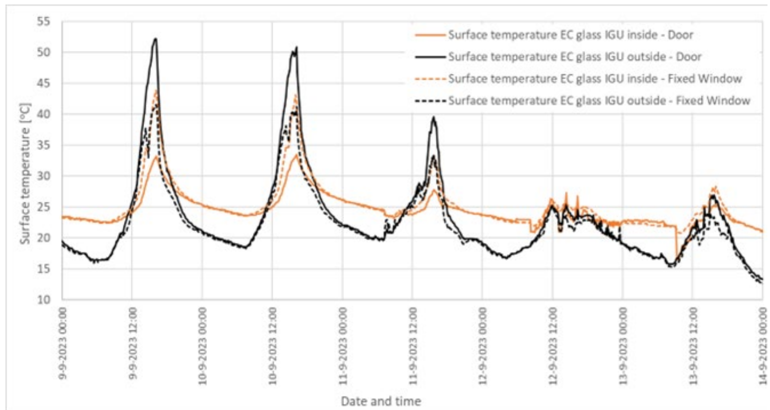




**Figure 3 (left).** Direct solar heat gains into the EC glass room and control room from Sept. 2023 - March 2024.
**Figure 4 (right).** Inside and outside surface temperature of the EC glass IGU installed in the middle window (EC coating on glass pane closest to the indoor environment) and in the door (EC coating on glass pane closest to the outdoor environment), for five selected days in September 2023.

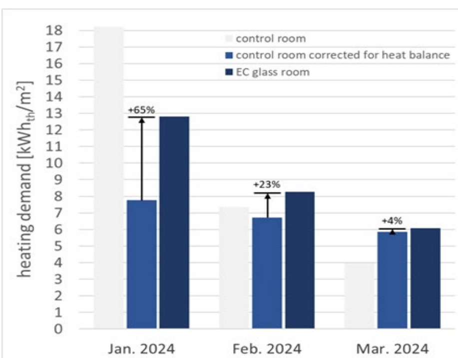
## 3. RESULTS AND DISCUSSION

### 3.1. Incoming solar radiation and surface temperatures

The direct solar heat gains for the months Sept. 2023 till March 2024 are presented in Figure 3. These results are based on the output of the indoor pyranometers behind the glass and normalised by the floor area of the room. The direct solar gains through the EC glass IGU are much smaller than through the standard IGU. On average, this difference is 81%, with monthly variations from 72-94%. This means that $t_{sol}$ of the EC glass IGU is much smaller than of the standard IGU. However, this does not reflect the difference in total solar heat gains, for which also the indirect component due to absorption and re-emission of heat by the EC coating needs to be considered.
Therefore also the indoor and outdoor surface temperature of the EC glass IGUs were monitored. Figure 4 shows five selected days in September 2023. These measurements show that the absorptive EC coating heats up when exposed to direct solar radiation. During the entire measurement campaign, for the IGU with the EC coating integrated into the glass pane closest to the indoor environment, a peak indoor surface temperature of 49.1 ºC and a peak outdoor surface temperature of 45.7 ºC were measured, but not at the same time. For the IGU with the coating integrated into the glass pane closest to the outdoor environment, a peak indoor surface temperature of 33.5 ºC and a peak outdoor surface temperature of 55.7 ºC were measured, also not at the same time. These high temperatures were recorded when the glass was in tinted state. As a result, the indirect solar gains can be high and, even though the direct solar transmission may be limited, the overall solar heat gain coefficient can still be high.

### 3.2. Effect of EC glass on heating demand

The months January till March 2024 gave the most reliable data regarding the energy demand for heating. In December 2023, a better air temperature control algorithm was implemented. During these months the heating setpoints were working properly and the average air temperature in both rooms was close to identical, except for January (Figure 6). The heating demand of the room with the EC glass IGU was higher than of the corrected one of the room with the standard IGU, even though the U-value of both were identical. On average, the energy demand for heating in the experimental room was 34% higher than in the control room, with monthly variations from 4-65% (Figure 5). Besides, simulations in the software DesignBuilder v.7 were performed with a calibrated model of the test building and the exact same set-up of the experiment. These simulations showed for a full heating season that the EC glass IGUs increased the heating demand by 12% as compared to the original IGUs, assuming that in winter the glass was in clear state. The main reason for the increased heating demand is that the g-value of the EC glass IGU was lower than of a standard IGU. This reduces the solar heat gains in winter. This effect is stronger than the effect of the heating up of the absorptive layer. Besides, the smaller size EC panels with sealant seals in-between them reduced the 'transparent' area of the glass. The seams covered close to 10% of the glass. The impact of this on the U-value was small because they only appear in the innermost glass pane of the triple glass. However, they did reduce somewhat the direct solar gains.



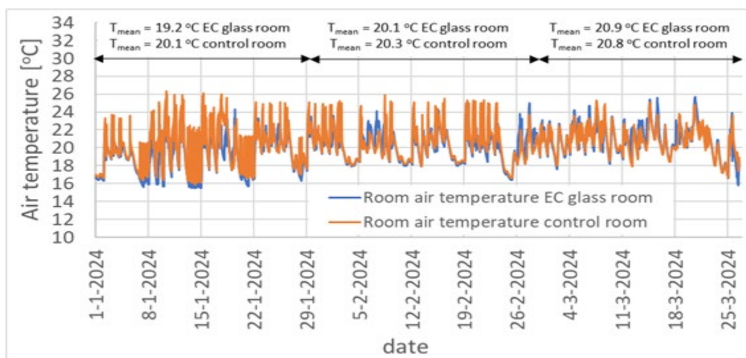
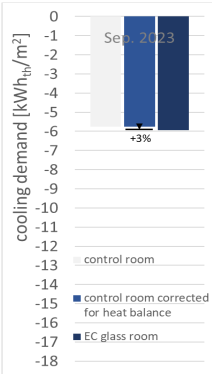




**Figure 5 (left).** Measured heating demand of the experimental and control room for January till March 2024.
**Figure 6 (right).** Measured air temperature in the experimental and control room from January till March 2024.

### 3.3. Effect of EC glass on cooling demand

Unfortunately, no proper monitoring was possible for the summer months because the prototype of the EC glass IGU was only operational from September 2023 onwards and during spring and summer 2024 the test building was undergoing construction works. Luckily, September 2023 had summer-like conditions (av. monthly max. temp. of 23.1ºC). During that month, the cooling demand of the experimental room was similar to that of the control room (Figure 7). A difference of 3% was observed but the absolute value of this difference falls within the measurement uncertainties. Simulations with the calibrated model in DesignBuilder showed that for a full cooling season the EC glass IGUs decreased the energy demand for cooling by 9% as compared to the original IGUs without active sun-shading, and increased the cooling demand by 44% as compared to the original IGUs with active dark outdoor roller blinds (active if solar radiation on façade >125 W/m$^2$). These results are in line with other studies, albeit slightly lower. For instance, Chambers et al. (2019) found that EC glass could lead to a reduction of 11% in the cooling and lighting demand in Swiss office buildings. Krarti (2022) concluded that EC glass with optimal switching control could lead to an energy reduction of up to 20% for office buildings relative to static glazing. A point of attention in our study are the smaller than full size EC panes and the resulting sealant seals between the panes. The impact on the cooling demand is difficult to assess because the direct solar transmittance and the temperature of these seams were not measured.



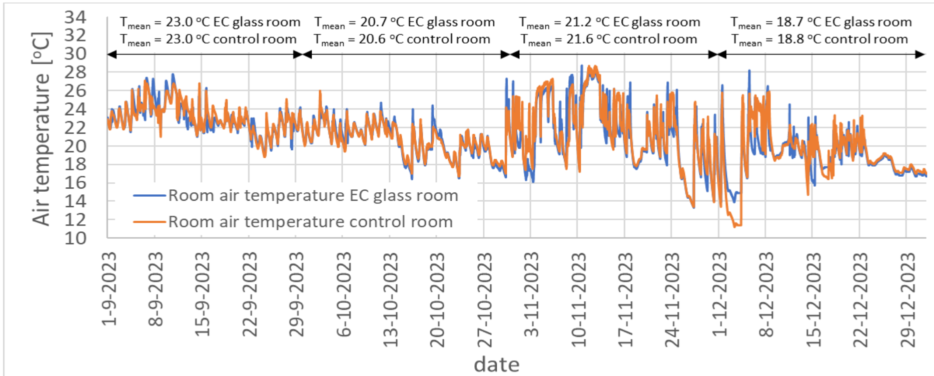




**Figure 7 (left).** Measured cooling demand of the experimental and control room for September 2023.
**Figure 8 (right).** Measured air temperature in the experimental and control room from Sept. till Dec. 2023.

## 4. THERMAL AND VISUAL COMFORT

Besides the extensive monitoring and simulation campaign, an experiment was done as a repeated measures "within subject" study with a total of 38 participants. The participants were spending in total two hours in the two rooms, i.e., the control and the experimental room. They were exposed to different conditions in random order and were working on a reading task. During the first 30 minutes, the EC glass was in clear state in the experimental room or the roller blinds were up in the control room, without sun in the field of view. Then the glazing was tinted or the blinds were lowered for another 30 minutes with the sun in the field of view. Then the glass was bleached and the blinds raised for another 30 minutes. At the end of each 30-minute session, the participants were asked to complete a questionnaire on their perceptions of the visual and thermal environment. The experiment showed that in general in dark state (EC glass tinted or blinds down), satisfaction with view clarity, daylight colour and daylight availability was higher for the EC glass IGUs (Figure 9). In transparent state (EC glass clear or blinds raised), no significant difference was perceived, except for view clarity. Overall, the EC glazing was perceived by the participants as a good alternative to dark roller blinds. More details can be found in Luna-Navarro et al. (2024).

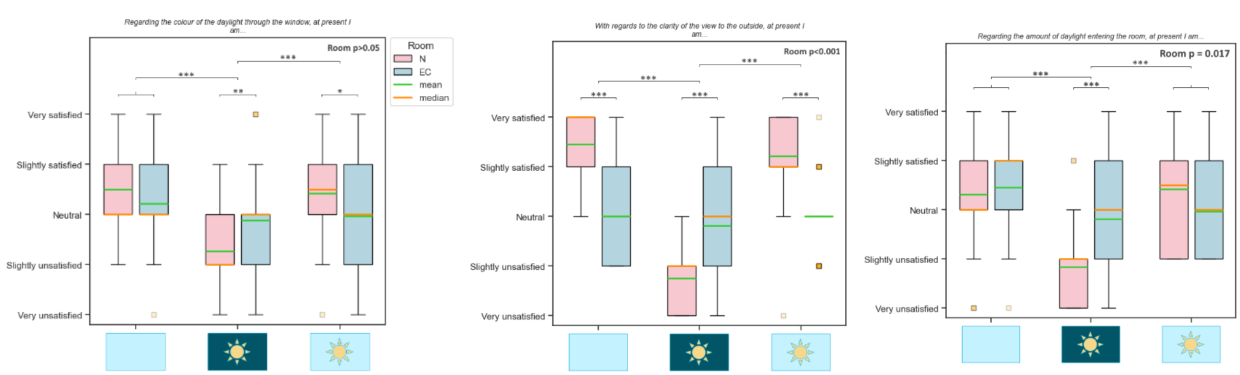



**Figure 9.** Results from the assessment of the user satisfaction with the visual environment. **left:** satisfaction with the daylight colour in the room; **centre:** satisfaction with view clarity; **right:** satisfaction with the amount of daylight in the room. The level of significance is: * = p-value < 0.05; ** = p-value < 0.01; *** = p-value < 0.001.

## 5. CONCLUSION

This paper presented some of the results of the Windows to the Future project, a project on the application of low-cost inkjet-printed electrochromic (EC) glazing and focussed on the results of the monitoring campaign. Prototype EC triple glass IGUs were installed in the west façade of a meeting room and the heating and cooling demand of this room were compared to that of a control room with standard triple glass IGUs. The results showed that the EC glass IGUs led to a higher energy demand for heating in winter. This is mainly due to lower solar heat gains through the EC glass. Under summer-like conditions, the energy performance of the EC glass IGUs was found similar to that of the standard IGUs. Even though the EC glass IGUs had much lower direct solar gains, the heating up of the absorptive coating resulted still in high (indirect) solar gains. A key point to mention here is that the EC coating in the triple glass IGUs was placed on the glass pane closest to the indoor environment. For better performance in summer, this coating should be placed on the glass pane closest to the outdoor environment. Besides, a larger dynamic range (especially towards the upper range, i.e. higher transparency) would improve the glass's performance under winter conditions. Also, a controlled experiment with participants showed that in general in dark state, satisfaction with view clarity, daylight colour and daylight availability was higher for the EC glass IGUs. In transparent state, no significant difference was perceived, except for view clarity. Overall, the EC glazing was perceived by the participants as a good alternative to dark roller blinds. Furthermore, future research should increase the length of the monitoring campaign, and test different room orientations and control strategies for the switching of the EC glass, as these were limitations of this study.

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