Electrochromic smart windows are promising for green buildings due to energy efficiency, long optical memory effect, and tunable optical transmission. However, their wide application in buildings is impeded by challenges in scalability, cost-effectiveness, and limited optical contrast. Quantitative field study of energy savings enabled by electrochromic smart windows in buildings is also lacking. Herein, with the established inkjet printing procedures, electrochromic smart windows (900 cm²) are fabricated. With large optical contrast (~60%), fast switching kinetics (t₄ = 43 s, t₈ = 70 s), and long optical memory retention (transmittance <10% for 7 h), when installed onto the outdoor testbed, these electrochromic smart windows can effectively reduce the internal temperature, especially in summer tropical weather. The energy savings brought by electrochromic smart windows are found to be higher in sunny days than in rainy days. Specifically in a sunny day, the heat gain reduction can reach 42.3%, and for a comfortable targeted indoor temperature of 25 °C, the cooling load savings can be 28.9% compared to regular double-glazing units-based reference testbed. This study demonstrates the scalability of inkjet printing technique for fabricating large-area electrochromic devices and the substantial energy savings obtained from testbed results.

1. Introduction

The ever-increasing global mean temperature and greenhouse gas emissions have led to the importance and necessity of energy efficiency.[1] Buildings are reported to be responsible for 40% of global energy consumption and 30% of annual greenhouse gas emissions.[2,3] Heat gain by solar radiation through transparent windows has contributed significantly to the heat, ventilation, and air-conditioning (HVAC) energy consumptions in buildings.[3,4] Smart windows capable of modulating solar radiation can reduce the heating and cooling energy needs in buildings, and are thus deemed as promising solutions toward green buildings and energy sustainability.[3,4]

Smart windows operate based on different technologies, e.g., thermochromic, photochromic, mechanochromic, liquid crystal, and suspended particles. Among them, electrochromic (EC) smart window has the advantages of active control, large optical contrast, fast switching speed, and long memory retention.[3,4] EC smart windows can reduce up to 70% of building heat gain from solar radiation, and it is estimated that EC smart windows can reduce the lighting and HVAC energy consumption by ~20% in buildings.[3,5,6] Dominating the United States smart glass market, EC smart glass is predicted to reach more than 1/3 of the total smart glass market with estimated market size of more than 1 USD billion in 2024.[7]

Albeit the advantages and future promises, commercialization of EC smart windows is still in its infancy due to the issues related to scalability, cost-effectiveness, and limited optical performance.[5,8] The maximum market entry price for these smart windows is around 500 USD $ m⁻² and expected to be further reduced to 100 USD $ m⁻².[4,9] There have been a few successful commercialized EC-based smart windows, including Sage,[10] View,[11] Halio,[12] etc. However, the cost of EC smart windows is considerably high for many commercial and residential purposes, as the vacuum facilities employed for large-area electrode deposition have high operation costs.[13] Proliferous reports on EC smart windows in the literature are focusing on EC materials and multifunctionality, neglecting the challenges of scaling up.[3,14] Up to now, only a few reports demonstrated EC devices with area close to 900 cm², yet the optical performance of these large area EC windows was not evaluated in details.[3,15–18] The quantitative field study of energy savings brought by EC smart windows is also lacking.
Aiming at cost-effectiveness and ease of scalability, liquid-phase inkjet printing technique was selected herein to produce large-area EC electrodes for field studies. Inkjet printing is a powerful tool for producing highly uniform and large-area thin films with controllable thickness and patternability.\textsuperscript{[19,20]} In our previous works, inkjet printing has been adopted to print both continuous and noncontinuous (patterned images) NiO- and WO\textsubscript{3}-based EC films on various substrates.\textsuperscript{[19–21]} Here, multiple EC devices with area of 900 cm\textsuperscript{2} have been assembled with inkjet-printed EC films. These inkjet-printed large area 900 cm\textsuperscript{2} EC smart windows exhibit large optical contrast (ΔT\%≈60\%), fast switching ($t_\text{c} = 43\text{ s}$, $t_\text{b} = 70\text{ s}$), and long optical memory retention (7 h with 7\% < 10\%). To study the energy savings enabled by EC smart windows, these EC devices were mounted onto a regulation-compliant outdoor testbed. Compared to the reference testbed, the internal temperature in EC testbed is obviously lower under different weather conditions, especially during the hot midyear weather in Singapore (month of May), demonstrating the effective energy savings in heat gain and cooling load enabled by EC smart windows. Specifically, the heat gain reduction can reach 42.3\% in a sunny day, higher than that in a rainy day (26.7\%). With the targeted indoor temperature of 25 °C, the cooling load savings can be as high as 28.9\%, compared to only 16\% in a rainy day.

2. Results and Discussion

Following our previously developed inkjet printing procedures,\textsuperscript{[19,20]} WO\textsubscript{3}-based EC films are successfully printed on 30 × 30 cm\textsuperscript{2} transparent conductive oxide (TCO) glass. The WO\textsubscript{3}-based EC electrodes were assembled into an EC device with a TCO counter electrode, sandwiching gel electrolyte in between the two electrodes. To achieve optimum optical performance (e.g., high transparency at clear state, large optical contrast, and fast switching kinetics), the thickness of WO\textsubscript{3} was controllably adjusted by tuning the number of printing layers. The spectrum and switching kinetics of EC devices assembled with electrode printed with 3 layers of WO\textsubscript{3} inks (EC-3L) were collected as shown in Figure 1. The spectrum of EC devices (EC-2L and EC-4L) assembled with different layers (2 layers and 4 layers) of WO\textsubscript{3} is also analyzed in Figure S1, Supporting Information. Compared to the spectrum of EC-2L and EC-4L (Figure S1, Supporting Information), EC-3L has a higher initial transmittance of 64.4\%. With increased number of printed layers, the achievable transmittance (633 nm) at colored states (−3.5 V) is lowered, indicating better light blocking ability. At colored state, EC-2L can only reach transmittance of 8.78\%, while EC-3L and EC-4L can achieve transmittance as low as 4.8\% and 1.65\%, respectively. With reverse bias, the transmittance of EC-3L can be restored back to 63.4\%, achieving good reversibility as shown in Figure 1a. However, EC-4L can only be partially restored to transmittance of 51.1\%. Therefore, the focus of studies will be on EC-3L which has demonstrated optimum transmittance contrast and reversibility. Switching time, the time needed to reach 90\% of the full optical modulation, is also a key parameter for EC devices, which can be affected by the voltage applied and the effective working area of the EC devices.\textsuperscript{[15,18,20]} For EC-3L, the switching kinetics (coloration time, $t_\text{c}$ and bleaching time, $t_\text{b}$) quantified accordingly ($t_\text{c} = 43\text{ s}$, $t_\text{b} = 70\text{ s}$) are relatively fast, which is much faster than the commercial EC windows (≥20 min, area > 1 m\textsuperscript{2}).\textsuperscript{[10–12]}

The optical performance of EC-3L is also compared with other reported EC devices in the literature with similar areas, as summarized in Table S1, Supporting Information. Although some have demonstrated larger area, these EC devices do not offer a highly transparent clear state, and the optical performance is only evaluated at a smaller scale.\textsuperscript{[17,18]} The other works demonstrated relatively fast switching in EC devices at similar scales (≈900 cm\textsuperscript{2}),\textsuperscript{[13,15,16]} yet the construction of those devices requires incorporation of metal mesh or a counter electrode, which in a way will also add onto the cost and device complexity.

Memory effect is also one of the key advantages of EC smart windows, which can maintain the colored state (low transmittance) without continuous voltage application, rendering EC devices energy-efficient candidates for smart windows. The memory performance of EC-3L was evaluated before being installed onto outdoor testbed. As presented in Figure 1c, the transmittance of the device dropped to less than 5\% with application of −3.5 V for only 110 s. Subsequently, under open-circuit potential the transmittance of the device gradually increased in the next few hours. After 25,000 s (≈7 h), the transmittance was still maintained at ≈10\%. Such an impressive memory retention was never achieved in up-to-date large-area EC devices and has fulfilled the requirements (memory retention of a few hours) of smart windows installed on buildings.\textsuperscript{[9]} The excellent memory retention performance of EC-3L was tentatively ascribed to the optimal WO\textsubscript{3} film thickness and the well-tuned controlled viscosity of the polymer electrolyte,\textsuperscript{[22]} which allows sufficient Li\textsuperscript{+} ions intercalation during coloration and, simultaneously, hinders ions diffusion at the open circuit potential, resulting in the robust, prolonged colored state of the EC device. To keep the transmittance of EC-3L less than 10\%, another short bias (−3.5 V, 50 s) was also applied to lower the transmittance to less than 5\%. As shown in Figure 1d, at colored state EC-3L shows a uniform dark-blue color that blocks most of the visible light, and it can be bleached back to a highly transparent state upon reverse bias. Considering the initial transmittance, optical contrast, switching kinetics, and optical memory retention, EC-3L is deemed as the optimized device for further studies.

Albeit numerous studies reporting EC materials/devices with improved optical performance, field study of actual energy savings brought by EC smart windows in buildings is seldom conducted due to the difficulty in scaling up the large-area EC smart windows, durability, and the unsatisfactory optical performance.\textsuperscript{[15]} With optimum EC performance and excellent memory retention, multiple EC-3L devices were fabricated and assembled. The coloration efficiency of EC-3L was calculated to be 52 cm\textsuperscript{2} C\textsuperscript{−1}, as shown in Figure S3a, Supporting Information. Insulated glass units (IGU, or sometimes referred as double-glazing units) based on EC-3L panels were fabricated and installed onto the outdoor EC testbed. Construction of IGU devices and testbeds can be found in Supplementary Note 1. The spectra of the EC-IGU device over the solar radiation wavelength range (300–2500 nm) were also calculated, as displayed in Figure S3b, Supporting Information. EC-IGU has a visible light transmission ($T_{\text{vis}}$ 380–780 nm) of 0.658 and solar transmission ($T_{\text{sol}}$ 300–2500 nm) of 0.415 at clear state, and the corresponding
solar heat gain coefficient (SHGC) of 0.502. At colored state, EC-IGU has a $T_{vis}$ of 0.027, $T_{sol}$ of 0.020, and SHGC of 0.185. As shown in Table S2, Supporting Information, these values are comparable to those commercial EC smart windows and the EC device reported in the literature.[10,11,23]

Based on the memory retention performance (Figure 1c), the first bias (−3.5 V) was applied at 7:00 am daily to color EC-3L-IGU devices for 110 s before sun rise, and the second bias, −3.5 V for 50 s, was applied 7 h later at 14:00 before the sunlight reaches the highest intensity in the afternoon. Coloration of the three EC-3L IGU devices was controlled simultaneously by a multichannel potentiostat. For comparison study, another testbed installed with bare IGU devices was also deployed as reference testbed. As shown in Figure 2, the testbeds were

Figure 1. a) Spectrum, b) kinetics, c) transmittance retention of EC-3L, and photographs of EC-3L at d1) colored and d2) bleached states.
constructed in a cube structure, with three sides (north-west, south-west, and south-east) installed with windows, supported by marine plywood base. The outdoor temperature, humidity, and the indoor temperature of the two testbeds were recorded continuously for further analysis. During the daytime, the IGU in the reference glazing testbed remains highly transparent, while the EC-IGU devices with the capability of active control offer relatively low transmittance at the colored state that can effectively block the solar radiation and thus lower the temperature inside the testbed.

Monitoring of the testbeds’ internal temperature was commenced in December 2020 and has been conducted for more than half a year to cover different local weather conditions in Singapore. As shown in Figure S4, Supporting Information, during the year end (north-east monsoon season), the outdoor temperature (recorded outside the reference testbed) in December is lower than 40°C for most of the time; the maximum temperature reached above 35°C only for a few days. On the contrary, in the midyear hot season of May, almost half of the daily recorded maximum temperature can reach >40°C, while somedays the maximum temperature is still below 35°C due to occasional afternoon rains. Clearly, the solar radiation in May is much stronger than the year-end December period. The daily temperature profiles inside the testbeds in May 2021 were plotted and compared as shown in Figure 3a. In the reference testbed, the internal temperature can easily rise above 35°C, as the IGU can hardly block the solar radiation. Nevertheless, the internal temperature in the EC testbed is always maintained lower than 35°C at the colored state, verifying the “cooling effect” of EC smart windows.

Given the different weather conditions in year-end and midyear, the cumulative frequency of testbeds’ internal temperature in different weather conditions was also plotted in Figure 3b,c. Clearly, the EC testbed is very effective in reducing the internal temperature compared to the reference testbed as evidenced by the lower temperature inside EC testbed at different percentile in both year-end and midyear. The “cooling” effect enabled by EC smart windows is more obvious in midyear. As tabulated in Figure 3d, 99% of the internal temperature is ≤33°C in EC testbed and is ≤44.5°C in the reference testbed in midyear. With lower outdoor temperature at year-end, 99% of the internal temperature in EC testbed is ≤34.5°C and is ≤40°C in reference testbed. It should be noted that there will be intermittent afternoon rains in midyear that caused similar daily temperature profiles in both EC and reference testbed, as can be found in Figure 3a.

For the long-term stability test, the EC performance of the EC-3L device was evaluated after exposing to the field test for 8 months. The outcome of the long-term stability test is shown in Figure S5, Supporting Information. After 8 months of outdoor exposure, optical contrast of 54.4% is still retained, with contrast retention of 98.7%, demonstrating excellent long-term stability of EC-3L device.

To quantify the energy saved by EC smart windows in midyear hot days, the internal temperature profiles of the testbeds in two representative days (sunny and rainy) were depicted in Figure 4a, b. In the selected rainy day (May 4, 2021), the heavy rainfall in the afternoon (a daily rainfall total of 28.44 mm) resulted in cooler temperature (no temperature spike). As shown in Figure S6, Supporting Information, in a typical sunny day (e.g., May 10, 2020, daily rainfall total of 0 mm) the outdoor temperature can rise to 60°C after 14:00, accompanied by synchronously decreased humidity. In a typical day with afternoon rain (e.g., 04 May 2021), the humidity suddenly rose after 15:00 while the outdoor temperature was maintained at <40°C. Following the trend of outdoor temperature in sunny day, the internal temperature in reference testbed also increases to 44°C in the afternoon, while the internal temperature in EC testbed is maintained at a significantly lower temperature of 33°C. In rainy days, the temperature profiles are rather similar for the two testbeds. To explain the effect of weather on energy savings brought by EC smart windows, the cooling load savings under different targeted
indoor temperature and the heat gain reductions are quantified in different weather conditions. As can be seen from Figure 4c, the cooling load savings brought by EC windows are generally lower in rainy days than in sunny days, as the outdoor temperature in rainy day is typically lower. The cooling load savings also increase with increased targeted indoor temperature. In sunny days when the outdoor temperature can be as high as 60 °C (Figure S6a, Supporting Information), the cooling load savings in EC testbed can be significantly higher. At targeted indoor temperature of 27 °C, there is a significant cooling load savings of 42.3%. For a more comfortable indoor temperature of 25 °C, the cooling load savings can still reach 28.9% in a typical sunny day, while in rainy day the cooling load saving is only 16%. As shown in Figure 4d, the heat gain in reference testbed is obviously higher than in EC testbed, especially in sunny day. In comparison to reference testbed, the heat gain reduction brought by the EC testbed in a sunny day can be as high as 42.3%, whereas it is only 26.7% in a rainy day. It should be noted that these values are based on the specific testbed design and for a typical day in Singapore. The indoor lighting, circulation, and air-conditioners in real buildings are also neglected. However, it undoubtedly verifies that EC smart windows can effectively reduce the energy costs in buildings. With issues of scalability and cost-effectiveness being resolved, EC technology will be implemented in green buildings and more.

3. Conclusion

With low-cost and scalable inkjet printing methods, large-area EC devices (900 cm²) have been successfully fabricated. These EC devices manifest high initial transparency (>65%), large optical contrast (>60%), fast switching kinetics (τc = 43 s, τb = 70 s), long optical memory retention (7 h with transmittance <10%), and excellent outdoor stability (98.7% contrast retention after 8 months field test), which outperforms most of the reported
EC devices at a similar scale. Moreover, outdoor testbeds were constructed for field studies using these EC devices. Based on the field studies, these EC devices can effectively lower the internal temperature in testbeds under different weather conditions. The heat gain reductions and cooling load savings enabled by EC smart windows are higher in sunny days than in rainy days. The heat gain reduction can reach 42.3% in a sunny day. For a comfortable targeted indoor temperature of 25°C, the cooling load savings can be as high as 28.9% in a sunny day, in comparison to only 16% in a rainy day. These values clearly demonstrated the effectiveness of our inkjet-printed large area EC smart windows in saving energy costs in buildings.

4. Experimental Section

Formulation of WO$_3$-Based Inkjet Printing Inks and the Gel Electrolyte: Formulation of WO$_3$-based inkjet printing inks was realized by dispersing WO$_3$ nanoparticles into mixed solvents with the help of surfactants. The detailed WO$_3$ synthesis and ink formulation procedure can be found in our previous works.[24] The gel electrolyte was formulated by dissolving Li salts into organic solvents with addition of PMMA. The detailed synthesis of this gel electrolyte was also stated previously.[25]

Large Format Printer: To facilitate the scalability of inkjet printing, an industry-scale printhead was employed to allow the scalable printing of WO$_3$ inks onto TCO (transparent conducting oxides) glasses (30 x 30 cm$^2$). After printing, the TCO electrode was dried at 60°C overnight. To attain low transmittance at the colored state while securing high initial transparency, samples were printed with 2 layers, 3 layers, and 4 layers (2L, 3L, and 4L) using the prepared WO$_3$-based inks. The printing resolution used was kept at 900 dpi. It should be noted that this printhead is capable of printing larger areas; attempts to print on larger TCO glass (50 x 50 and 100 x 100 cm$^2$) are ongoing.

Device Fabrication: With VHB spacer (3M) and epoxy-based sealants, EC devices were fabricated by laminating the printed working electrode with a bare TCO counter, sandwiching the gel electrolyte. The fabricated EC devices were named as EC-2L, EC-3L, and EC-4L based on the number of printed WO$_3$ layers on the working electrode.
windows under real weather conditions. The design and construction of testbeds need to fulfill the requirements of Building & Construction Authority of Singapore. To ensure the visual and thermal comfort of occupants, the window-to-wall ratio needs to be higher, while the envelope thermal transfer value (ETTV) should be below 50 W m$^{-2}$. The detailed process of testbed construction can be found in Supplementary Note 1.

**Measurements and Calculations** The optical properties of the EC devices were measured with UV–vis spectrometer (Shimadzu UV-3600 spectrophotometer); potential application was realized by Solatron 1470E. Note that the EC measurements were conducted at the center of the 900 cm$^2$ device. Outdoor temperature and testbed temperature collection was realized by a temperature data logger. Outdoor humidity was also recorded using humidity data logger. The testbed temperature profiles were collected at the center inside the cubic testbeds (see Figure S2, Supporting Information, for the testbed facings), and the outdoor temperature was collected at the outer surface of the north-west bare IGU device in the reference testbed. Quantification of energy savings (heat gain reduction and cooling load savings) was realized by calculating the heat load (energy needed to heat up the volume of air inside the testbed) based on the following equation

$$Q = m \times C \times dT$$  
(1)

where $Q$ is the heat load, $m$ is the mass of air, $C$ is the specific heat capacity of air, and $dT$ is the temperature difference between real temperature recorded inside the testbed and the targeted indoor temperature. $Q_{\text{ref}}$ and $Q_{\text{EC}}$ for different indoor temperatures were calculated and cooling load savings was calculated as $(Q_{\text{ref}} - Q_{\text{EC}})/Q_{\text{ref}}$. Heat gain reduction was calculated as $(Q_{\text{ref}} - Q_{\text{EC}})/Q_{\text{ref}}$ with a base temperature of 27°C (Figure 4a, at 8:00).

**Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.

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**Conflict of Interest**

The authors declare no conflict of interest.

**Data Availability Statement**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

**Keywords**

cooling load savings, electrochromic smart windows, field studies, heat gain reductions, inkjet printing

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