Solar Energy Materials & Solar Cells 156 (2016) 170–181

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Energy and emissions analysis of next generation electrochromic devices

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ARTICLE INFO

Article history:
Received 24 July 2015
Received in revised form
23 November 2015
Accepted 5 December 2015
Available online 21 January 2016

Keywords:
Nanocrystal-based ion conducting films
"Cradle-to-gate" energy and emissions analysis
Electrochromic windows
Solution-based processing

ABSTRACT

The impact of buildings on the environment, energy consumption and climate change is significant, as they use a large amount of resources across their life-cycle. Since windows play an important role in the overall energy and environmental performance of buildings, emerging technologies are focused on the optimization of these building components. Among window design technologies, electrochromic (EC) devices have received growing interest for their ability to dynamically manage the daylight and solar energy entering buildings. Near-infrared switching electrochromic (NEC) glazed windows use a novel EC window technology that is able to continuously provide high transparency while modulating solar heat gains. This study evaluated the manufacturing phase of NEC windows to understand if their use phase performance comes at acceptable manufacturing burdens. This study also identified which constraints are connected to the market shift to the novel technology, which can provide the research community with useful information to better design the technology as it develops. A comparative "cradle-to-gate" energy and emissions analysis was carried out between NEC and conventional EC windows.

The obtained results for the Global Warming Potential of the conventional EC device was 85 kg CO_2-eq/m^2 and the Cumulative Energy Demand was 1680 MJ-eq/m^2. Results for the NEC device were found to be 50 kg CO_2-eq/m^2 and 1050 MJ-eq/m^2, with the reduction primarily due to replacing the energy intensive thin film deposition used in conventional EC with a solution-based coating process. Finally, when an entire window is modeled (EC device, frame, glazing and sealing), the difference over conventional EC, in terms of primary energy consumption, ranged for the whole window manufacturing from 15% to 21%, depending on the material of the frame.

1. Introduction

The importance of embodied energy in buildings is growing as a consequence of several national and international programs that require reducing building energy consumption during the operative phase [1,2]. This is particularly true for Net Zero Energy Buildings, in which there is a risk of increasing the energy use associated with materials production and end of life management phases in order to reduce energy use during the operational phase [3]. Active and passive technologies, such as renewable energy systems or highly performing insulation materials and façade systems, have been introduced to save operation energy. Given the importance of windows for allowing daylighting and reducing heat infiltration and heat loss in efficient buildings, with up to 60% of the total energy loss of a building coming from its windows [4], thermal and solar transmittance coefficients, air tightness of the windows have been improved in recent years to limit the operational energy losses. Currently there are many fenestration systems that proved to have a large potential for improving window performance, such as the following: multilayer glazing, new spacer solutions, vacuum glazing, low emissivity (low-e) coating [5], solar cell glazing, aerogels, glazing cavity gas fills, frame with composite materials [6], phase change material window products, and smart windows that can change their properties to adjust to outside and indoor conditions [7].

When implementing new technologies, including windows, manufacturing impacts should be carefully addressed. According to Tarantini et al. [8], the environmental impact of production processes can range from 10% to 60% of the overall contribution. Among smart windows, Beatens et al. [9] found that electrochromic (EC) windows are a promising technology. They are able to improve the performance of the building envelope by reducing

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http://dx.doi.org/10.1016/j.solmat.2015.12.017
0927-0248/

cooling and heating loads as well as electric lighting demand [9]. Compared to a standard low-e window with shading, the application of EC windows can reduce daily energy consumption by 20–30% in many parts of the world [10]. However, the acceptance of EC coatings in the window market has been slow and the primary barrier to adoption is the cost [11]. In this regard, the current price of completed EC windows vary in a range of 860–1080 $/m^2 [12], while a study carried on in 2009 for residential application [13] estimated that EC windows will not be cost-effective in comparison with low-e capabilities until a price point of 215 $/m^2. The same study evaluated the cost of a competitive static window (low-e, low-SHGC, argon-filled) in 170 $/m^2.

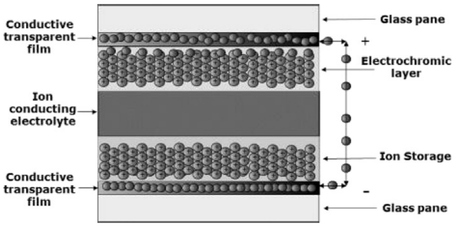
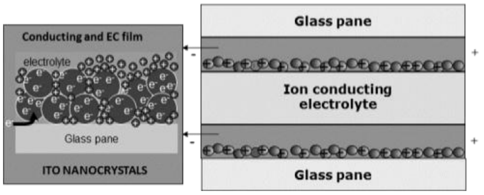
Conventional EC windows are based on metal oxide active layers combined with a polymer electrolyte and transparent electrodes deposited on glass surfaces [14]. When a low voltage is applied to the outer transparent conductors, ions migrate across the ion-conducting layer from an ion storage layer to the EC layer; the absorption of light by the active layer is fundamentally modified causing an opaque appearance of the glass. Reversing the potential, the ions migrate back, causing a transparent appearance [15]. One drawback to conventional EC windows is that they can limit the potential to harvest daylight when the window is opaque, and therefore on hot days an EC window reduces daylighting potential in order to reduce heat gain.

Near-infrared switching electrochromic (NEC) windows are a new technology that aims to address this drawback [16,17]. A NEC window differs from the conventional EC device in that the transmittance of near-infrared (NIR) radiation (52% of solar energy distribution) can be modulated without affecting the visible part of the spectrum, thus heat can be rejected while letting daylight pass through the window. As a result, in many U.S. regions, the combined savings of minimizing heat gain while maximizing daylighting can be on the order of 10% over the highest performing low-e windows [18]. The best performing locations include medium offices and midrise residential buildings in northern climates, where energy savings per unit window area range from 50 to 200 kWh/m^2 yr [19]. NEC windows are based on important modifications in the conductive transparent oxide layer (TCO): instead of the most widely used oxide thin film, metal-oxide nanocrystals, such as indium tin oxide (ITO NC), are prepared in solution and applied to a pane of glass or on a flexible substrate.

Table 1 summarizes the main characteristics of both conventional EC and NEC devices.

Previous studies have quantified the environmental impacts of conventional EC glazing production [20–23]. These studies found that the highest energy consumption in the conventional EC device processing (without considering framing) is due to active EC layer deposition on the glass pane. High manufacturing costs are closely related to the current complex and energy intensive coating techniques [24]. Typically, metal thin films are deposited using vacuum-based techniques, such as evaporation or sputtering or chemical vapor

Table 1
Comparison between conventional EC and NEC devices [9,10,12,18,7].

	Conventional EC device	NEC device
Layers		
How they operate	The transparent or opaque states transmit and block the entire electromagnetic spectrum, including the ultraviolet, visible and near-infrared wavelengths of light [10]	The “transparent or opaque” states transmit and block only the near-infrared (NIR) radiation, leaving the visible wavelengths untouched
Technology	Electrochromic film, typically WO_3-layer but also (oxides based on W, Mo, Ir, Ti, V, Ni, Nb) [9]	No need for traditional active EC layer: ITO NC has both conductive and EC properties
Main features	While in opaque state: – control over building heating and cooling loads – reduction of daylight levels	While in opaque state: – control over building heating and cooling loads – reductions in the use of interior lighting
Cost	(860–1080$/m^2) [12]	Unknown but expected lower than conventional EC [12] because lower manufacturing costs are expected
Switching Speed*	30 min/m^2 *large device tend to have long switching time	<1 min/m^2
Durability	10 s of thousands of cycles [12] but the switching range decreases [10]* Windows by Sage [7]: 10^5 cycles and 30 years within the range of −30 to 60 °C, 10 years guarantee. *The act of intercalation, that is responsible for switching in conventional devices, damages the crystalline structure of the active layer and eventually degrades the windows performance.	Unknown but better than conventional EC [12] It was estimated that the charge capacity changed approximately 4% over the first 2000 cycles [33]
Energy savings operating phase over low-e window	5% [34]	Unknown, but initial analysis indicates up to 10% [18]
Manufacturing costs	High temperature, energy intensive technique	Low-temperature, solution process technique
Esthetics	Poor esthetics: opaque appearance	Excellent visible transparency
Glare control	Blinds or curtains are not required	Shading needed
Maximum window size	1.6–2.6 m^2 [9]	Unknown
Electrical demand for Switching	0.5 Wh/m^2 [7]	Switching Power[a] 82.5 W/m^2. Assuming 10 s for the switching time the electrical demand is estimated in 0.23 Wh/m^2
Electrical demand	5 V [7]	Range 1.5 V–4 V (voltage over a range of 2.5 V) [33]
Example Manufacturers	SAGE Electrochromics, EControl-Glas and Gesimat [9]	/

[a] Personal communication with an expert (with Guillermo Garcia of Molecular Foundry-LBNL-2011).