10 Eco-efficiency analysis of an electrochromic smart window prototype

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Abstract

The environmental efficiency of a prototype electrochromic window was studied using eco-efficiency methodology, combined with life cycle assessment. The data obtained on the specified eco-efficiency indicators provide significant information that could be used in decision-making for the optimisation of the window's energy and environmental performance. The energy efficiency of the product is affected by its life expectancy and the climatic zone. It was found that in cooling-dominated areas the energy needs of buildings can be reduced by more than 55%, while the total energy saved can be 30 times the energy consumed during an expected 25 years life cycle. The corresponding CO_2 and human toxic emissions reductions were estimated to be 6 times those achieved with a conventional double-glazed unit. An expected retail price of 200 euros per m^2 for an electrochromic window would result in a cost of less than 0.10 euros for each kWh saved over a 20-year lifetime. Consequently, purchase cost reduction will be necessary if such devices are to meet market expectations for solar control window products.

10.1 Introduction

Windows incorporating electrochromic (EC) films have been evaluated as a promising subject for research into advanced glazing materials

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(Grandqvist 1995; Karlsson et al. 2001; Sbar et al. 1999; Selkowitz 1994). An EC window is an active solar control device whose transmittance in the visible and near IR parts of the spectrum can be reversibly modulated by applying a low voltage (typically 3–5 V DC). A typical EC device has a 5-layer structure consisting of (1) a transparent and electrically conductive film (ITO) deposited on glass, (2) an electrochromic film (usually tungsten oxide – WO_3), (3) an ion-conducting electrolyte (either a polymer or a solid state compound), (4) an ion storage layer and (5) a second transparent conductive film (Grandqvist 1995). Devices using polymer electrolytes require two glass sheets, one with the ITO/electrochromic oxide and the other with the ITO/ion storage layer. The polymer electrolyte can serve as the laminating medium that holds together the two coated glass sheets. When the external voltage is applied, the lithium ions move into the electrochromic oxide matrix, thus altering its optical properties. The general characteristics, energy benefits and potential savings ensuing from the use of EC windows are summarised in Figure 10.1 (Granqvist 1995; Papaefthimiou et al. 2006; Syrrakou et al. 2005).

An EC window:

- ⇨ has infinite coloration stages
- ⇨ ensures acceptable visual transmittance
- ⇨ can block both direct and diffuse solar radiation
- ⇨ reduces glare and thermal losses
- ⇨ has no maintenance costs (no moving parts)
- ⇨ requires low voltage power supply
- ⇨ provides architects a choice for a "living" building envelope
- ⇨ reduces cooling, heating and ventilating loads
- ⇨ reduces electric lighting
- ⇨ reduces *GHG* emissions

Figure 10.1 Electrochromic window prototype in the coloured state

The system we studied is a 40 × 40 cm EC device, which comprises the five typical layers. Two Pilkington K-Glass™ sheets (called K-Glass hereafter) serve as the transparent conductor. One is coated with the optically active layer, a 350 nm thick WO_3 film deposited by electron gun deposition, while the ion storage layer, a lithium-doped vanadium pentoxide film

($Li_yV_2O_5$) with a nominal thickness of 110 nm is thermally evaporated onto the second K-Glass sheet. The cavity created by these two sheets is then filled with the polymer electrolyte (in a 1.5 mm layer) which is prepared using a solution of a lithium salt mixed with a polymer: lithium perchlorate diluted in propylene carbonate and polymethyl methacrylate ($LiClO_4$ – PC – PMMA). The whole device is peripherally sealed by a silicone sealant to avoid water contamination. A third glass sheet can be integrated (with air or inert gas filling the cavity) to form the final window. The device has luminous transmittance values in the bleached and coloured states of 63% and 2%, respectively, with a coloration efficiency of 50 cm^2/C (see Figure 10.1).

This study used life cycle assessment (LCA) methodology to assess the eco-efficiency performance of the above EC window. The energy efficiency of the device was evaluated by means of environmental performance indicators, to ascertain whether it fulfils its goal as an energy-saving device. Throughout the life cycle analysis we also checked whether it is an environmentally benign product that can really replace conventional glazing to reduce the energy consumed for thermal comfort within a building envelope.

10.2 Methodology

The main objective of the study was to conduct a complete and detailed energy and environmental performance assessment for the prototype EC device. Eco-efficiency is a method to obtain results for both the environmental and economic performances of a product (or process) that can be used in decision-making on investments, product improvement, product selection or public policy. In order to measure and report ecological efficiency, the World Business Council for Sustainable Development recommends the use of indicators based on the balance between economy and environment. Each part of an indicator can be expressed positively or negatively: as value or cost for the economic aspect or as improvement or damage for the environmental aspect. The most appropriate way to define the eco-efficiency indicators is by combining the cost with the environmental improvement and the economic value creation with the environmental damage (International Eco-Efficiency Conference 2004, National

Table 10.1 Eco-efficiency indicators selected for the evaluation of the EC glazing

	Indicator's name	Definition	Units
R_1	Reduction of the building's energy needs	$\frac{\text{Total (heating and cooling) energy savings}}{\text{Single glass energy loads}}$	[%]
R_2	Energy efficiency of production	$\frac{\text{Total energy saved}}{\text{Net energy input}}$	[MJ/MJ]
R_3	Greenhouse gas (GHG) emissions reduction	$\frac{\text{Avoided GHG emissions due to energy savings}}{\text{EC unit}}$	[kg eq. CO_2]
R_4	Human toxic emissions reduction	$\frac{\text{Avoided toxic emissions due to energy savings}}{\text{EC unit}}$	[kg eq. 1,4-DCB]
R_5	Cost intensity	$\frac{\text{Additional purchase cost of EC unit}}{\text{net energy gains (savings - energy input)}}$	[euro cent/MJ]

Round Table 2001). This results in environmental performance indicators based on material and energy balances: raw material used per unit of product (kg/unit); energy used annually per unit of product (MJ/1000L product); energy conserved (MJ); hazardous waste generated per unit of product (kg/unit); emissions of specific pollutants to the air (tonnes CO_2/year) and wastewater discharged per unit of product (1000 L/unit) (see: ISO 1999).

An eco-efficiency analysis of a product would require evaluation of its entire life cycle according to the LCA method. This is an instrument for studying the impacts of a given product over all stages of its life cycle: resource extraction, energy use, production, distribution, use and ultimate disposal (Tyteca 1996). We applied the LCA methodology to the EC glazing we studied, distinguishing four phases according to ISO 14040: (i) goal and scope definition, (ii) inventory analysis, (iii) impact assessment and (iv) interpretation (see: ISO 2000). The goal and scope definition of the LCA provides a description of the product system and its boundaries related to a functional unit. The life cycle inventory analysis (LCI) estimates the consumption of resources (raw materials and energy) and the quantities of waste flows (air, liquid and solid emissions) that are attributable to the product's life cycle. In the next phase of the LCA, the life cycle impact assessment (LCIA) assesses the potential contributions of the inventory data (inputs and outputs) to a number of potential impacts, such as climate change, toxicological stress, eutrophication, etc. The impact categories included in the present study were global warming and human toxicity. The indicators for these two categories, calculated according to the CML guide, were expressed in equivalent kg of CO_2 emissions and equivalent kg of 1,4-DCB emissions per functional unit, respectively (CML 2001).

The LCI analysis and the LCIA yielded the energy data and the results for the impact categories that were needed to calculate the eco-efficiency indicators (SimaPro 2005). These indicators (summarised in Table 10.1) were defined so as to validate the environmental profile of the EC glazing, and are mainly oriented towards the assessment of the energy-saving capabilities and cost-intensity of the system compared to a single–glazed window (the reference case).

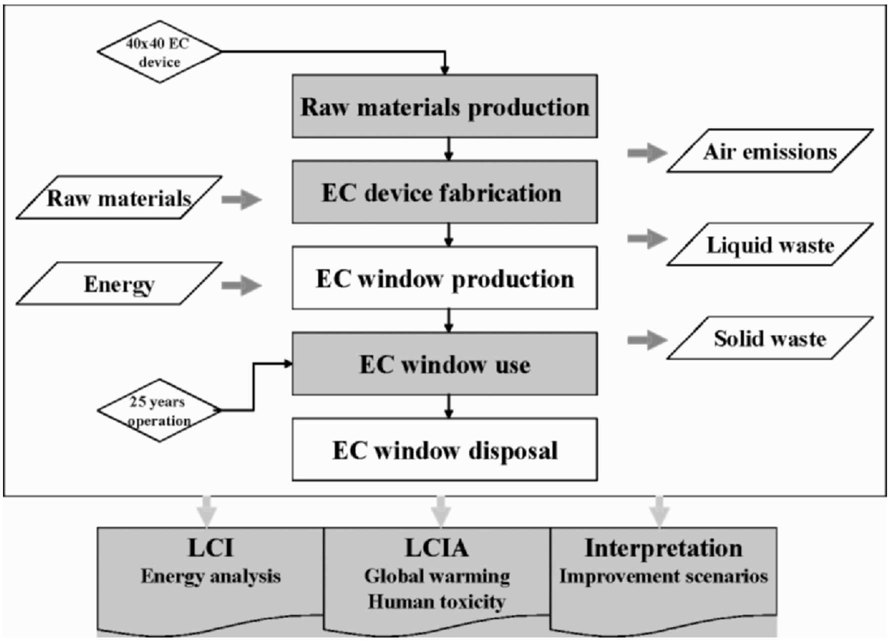

Figure 10.2 System boundaries for the LCA analysis of the EC window

10.3 Life cycle data processing

The functional unit for the LCA study was a typical 40 × 40 cm EC device as described in section 10.1. The system boundaries for the current LCA study are depicted in Figure 10.2, including the phases of production of the raw materials, production of the EC device components, assembly and use. Device disposal and transport were not taken into account. The LCI analysis resulted in a report on the inputs and outputs (energy and substances) for the manufacturing processes and the raw materials production for each part of the device (K-Glass, tungsten oxide, vanadium pentoxide, acetic silicone sealant, lithium perchlorate, propylene carbonate and PMMA; see Syrrakou et al. 2005). In particular, our energy inventory analysis included all the associated energy inputs: the energy embodied in the raw materials production, the energy required for manufacturing and the energy consumed during operation. It was estimated that 180 MJ of primary energy are required for the production of the plain 40 cm × 40 cm EC device prototype, 30% of which is allocated to the primary energy of raw materials and the rest to the electricity consumed during the various manufacturing processes. Only 0.01 kWh are required for the annual operation of the EC unit (Papaefthimiou 2006).

We calculated the reduction of the annual space heating and cooling requirements of a building during the operational lifetime of the device, in order to allow a comparison between the energy spent and saved throughout the anticipated lifetime of the glazing. Our analysis refers to buildings with large facades, located in three characteristic climatic types (cooling-dominated, heating-dominated and moderate areas) which were assumed to replace their single glass windows (SG) with EC glazing. The heating and cooling energy savings were calculated using the RESFEN 3.1 simulation package, for the plain EC glazing and for an alternative type equipped with a spectrally selective coated third glass sheet (EC_{ss}) (see: RESFEN 1999). The control strategy we implemented was based on an evaluation of the desirable ratio between the time that the EC window should be in the coloured and bleached states during the four seasons of the year, finally resulting in the window being maintained mostly in its bleached state during the cold season and in the coloured state during the hot season. The performance of the EC glazing was compared with that of a typical double–glazed unit (DG) and a double–glazed unit equipped with a spectrally selective

Table 10.2 Properties of the glazing types

Window	Description	U-value [W/m^2 K]	SHGC [a] [bl / col]	T_{lum} [b] [bl / col]
SG	1 gl 4mm, clear	5.8	0.74	0.74
EC	K-Glass 4mm / layered EC component / K-Glass 4mm/ air filled gap 9.5 mm / 1 gl 4mm, clear	1.8	0.46/0.10	0.66/0.06
EC_{ss}	K-Glass 4mm / layered EC component / K-Glass 4 mm/ air filled gap 9.5 mm / 1 gl 4mm, spectr. sel. low-e	1.8	0.38/0.10	0.60/0.05
DG	2 gl 4mm, clear, air filled gap 9.5 mm	2.4	0.68	0.67
DG_{ss}	2 gl spectr. sel. low-e, low solar gain 4mm / argon filled gap 13mm	1.40	0.38	0.57

[a] SHGC : solar heat gain coefficient; [b] T_{lum}: luminous transmittance

low-e coating (DG_{ss}), (typically one of the best and most commonly applied solutions in hot climates). The properties of the glazings we studied are listed in Table 10.2, and are based on the assumption that they are operative over a lifetime varying between 10 and 25 years.

In the LCIA stage, we assessed the contribution of the energy savings achieved to the reduction of global warming and human toxicity emissions. We used the electricity energy mix for Greece, where 1.21 kg of equivalent CO_2 emissions result from each kWh used for cooling. As far as the heating energy system is concerned, it has been estimated that 72.3 g of equivalent CO_2 are emitted per MJ of heat produced from natural gas processing (SimaPro 2005).

10.4 Eco-efficiency analysis

The following sections summarise the results of our analysis of the eco-efficiency indicators, comparing the performance of EC with that of other

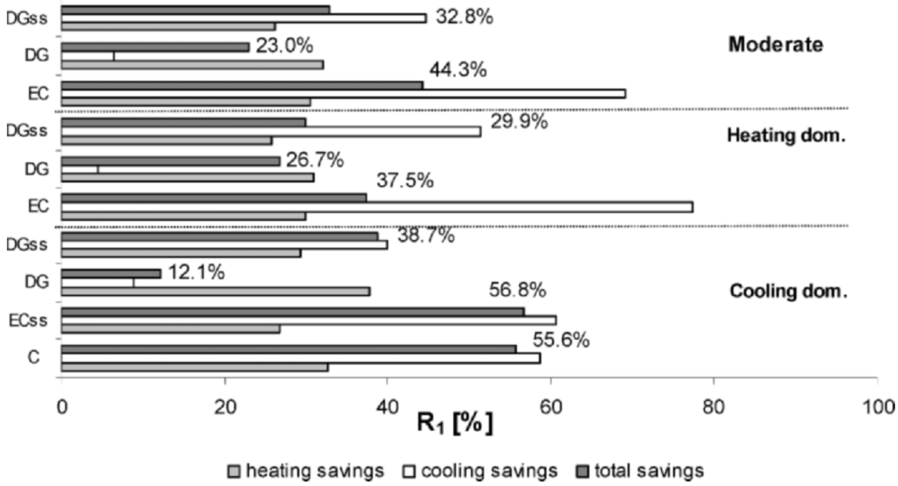

Figure 10.3 Reduction of energy needs of a building R1 with EC and DG glazing

types of glazing. The parameters used for this evaluation were: climatic zone, life expectancy and expected purchase cost.

Reduction of energy needs in buildings

The contribution of the EC glazing to the reduction of the total energy requirements (space heating and cooling) was investigated using the indicator R_1. The use of these fenestration products in cooling-dominated areas can reduce the annual space heating and cooling requirements of a building by more than 50%, as is depicted in Figure 10.3, indicating their high energy performance compared to DG.

The use of EC glazing is to be preferred in cooling-dominated areas, where maximum savings of 5608 MJ per EC unit can be achieved by using EC glazing instead of single-glazed units for a period of 25 years. These savings are attributed to cooling and heating loads reduction, equal to 127.1 kWh/m^2 glass per year and 94.3 MJ/m^2 glass per year, respectively.

Energy efficiency of production

Energy efficiency of production (R_2) is defined as the ratio of energy saved to the total energy used during the life cycle of a device. As depicted in

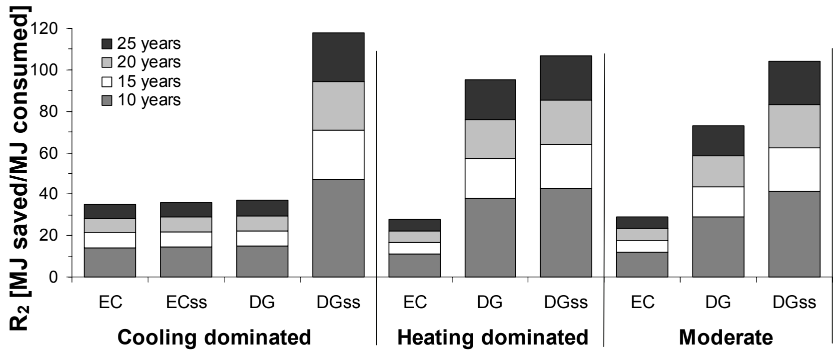

Figure 10.4 Variation in the energy efficiency of production (R_2) for the glazing types studied

Figure 10.4, the energy saved is 30–35 times the energy spent to produce and operate the EC device. The R_2 value for the EC glazing approaches that of the DG only for the cooling-dominated area, while DG_{ss} outperforms the EC in all cases. The reason for this is the fully industrialised production processes for the DG glazing, which reduce the energy input for their production. A possible penetration of EC technology in the glass market will result in incorporation of their production in the online glass industrial processes, thus significantly increasing their energy efficiency of production.

CO_2 and toxic emissions reduction

The reduction of the cooling and heating energy requirements in buildings resulting from the use of advanced glazing provides a strictly environmental benefit: the avoidance of GHG and toxic emissions due to electricity production (used for cooling) and the use of natural gas (for heating). Figure 10.5 depicts the variation in indicators R_3 and R_4 (reduction of GHG emissions and human toxic emissions, respectively) for 25 years of glazing use. The significant contribution of EC glazing to the reduction of GHG and toxic emissions is obvious in the three climatic regions. The emission of more than 600 kg of CO_2 eq. is prevented by the use of EC glazing in cooling-dominated areas. This value is six times larger than the corresponding

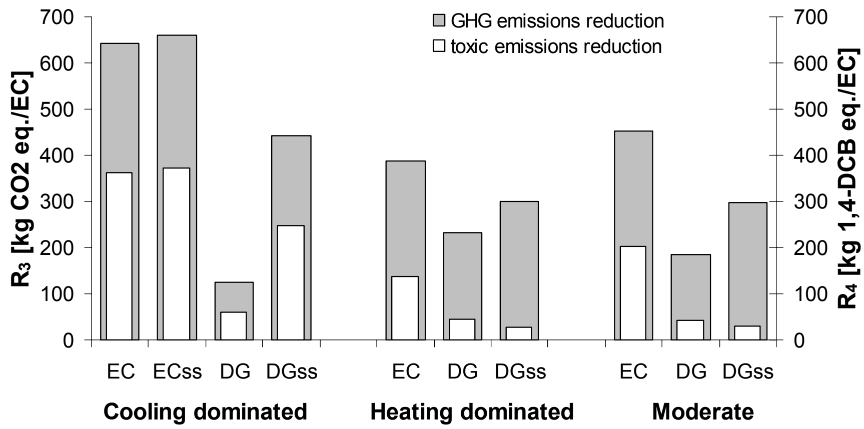

Figure 10.5 Variation in reduction of GHG and human toxic emissions (R_3 and R_4 respectively)

value derived for the use of DG. The corresponding toxic emissions reduction is about 350 kg eq. 1,4-DCB, while the EC_{ss} performs even better.

Cost intensity

Finally, indicator R_5 determines the cost of the net energy gains, expressed in euro cents per MJ of energy gained. The purchase cost of EC glazing is a matter of concern and remains a drawback for its market expansion. A range of prices between 200 and 800 €/m^2 for the EC glazing is examined in Figure 10.6, while DG is currently available at only 30 €/m^2. It is remarkable that increasing the lifetime of the EC glazing to 20 years ensures that the cost per MJ of energy saved is significantly decreased, to less than 1.07 euro cent, which is the current price of electricity in Greece.

10.5 Conclusions

We have evaluated the energy efficiency and environmental impact of an advanced glazing system, consisting of a prototype electrochromic device,

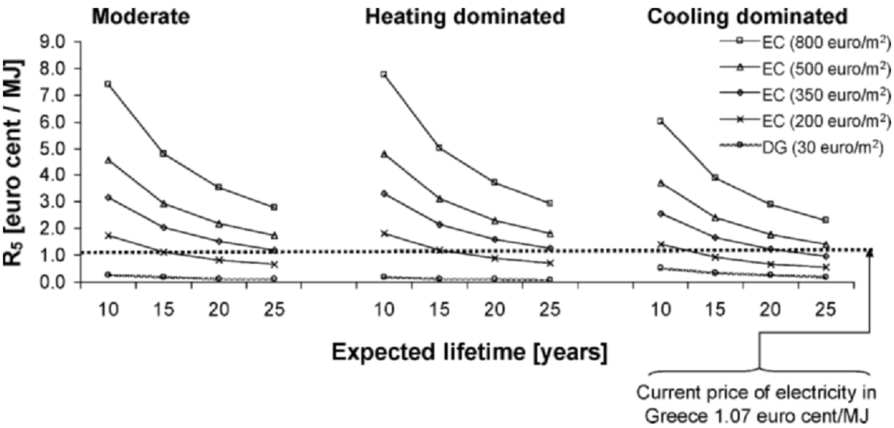

Figure 10.6 Variation in cost intensity (*R_5*)

employing suitable eco-efficiency indicators and LCA methodology. Such a glazing system can significantly reduce space cooling and heating requirements by replacing the commonly used single-glazed units in buildings, thus acting as an energy-saving component. We selected scenarios for improved control strategy of EC devices implemented in buildings located in three climatic areas, assuming lifetimes ranging between 10 and 25 years. It should be possible to achieve energy savings of 127.1 kWh/m2 glass per year and 94.3 MJ/m^2 glass per year for cooling and heating load, respectively, reducing the energy needs of a building by 55% when the EC device is used in cooling-dominated areas. The corresponding CO_2 emissions reduction is estimated to be more than 600 kg CO_2 equivalent, while the reduction in human toxicity emissions to the air could reach 350 kg 1,4-DCB equivalent, proving the energy benefits and the environmentally benign behaviour of these glazing systems. The energy efficiency of production reaches its maximum value (more than 30 MJ saved per MJ consumed) when the EC glazing is used in cooling-dominated areas and its life cycle is extended to 25 years. Furthermore, if the life cycle is extended to more than 20 years and the device price is reduced to 200 €/m^2, each MJ saved would cost less than the current electricity price (1.07 cent/MJ). This reduction of purchase cost and increased lifetime are the two main targets for achieving both cost and environmental efficiency.

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