Electrochromic Windows: Physical Characteristics and Environmental Profile

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Abstract. We present the thermal and optical evaluation of a 40 cm × 40 cm electrochromic window prototype mounted on an Insulating Glass Unit (double glazed window with a low emittance coating). The favorable optical performance of the electrochromic part combined with the excellent thermal protection of the advanced Insulating Glass Unit provides a product suitable for energy efficient applications. The environmental evaluation of the prototype was assessed by implementing the Life Cycle Assessment methodology. Energy savings up to 5608 MJ per unit can be achieved when the electrochromic device is used in cooling dominated areas and buildings with large facades. This corresponds to cooling and heating savings of 127.1 kWh/m^2 glass per year and 94.3 MJ/m^2 glass per year respectively. The reduction in building energy needs reaches 55.7% and the energy pay back time is only 0.8 years since the embodied energy represents only 3.3% of the energy saved during its life cycle. The net greenhouse gas emissions reduction is estimated to be 630 kg CO_2 equivalent, while only 0.5 years of operation are required to compensate the lifecycle emissions. Net human toxic emissions reduction can reach 358 kg 1,4-DCB equivalent, compensating its life cycle toxic emissions already from 0.25 years of operation.

1. Introduction

Electrochromic (EC) devices have gained considerable interest [1], because of their potential applications especially in advanced glazing. This research effort has resulted in the commercialisation of variable reflectance mirrors for automobiles and of variable transmittance glazing (smart windows) [2].

However, there are still many issues to be resolved in this field, the most important one being the exact knowledge of the mechanisms that generate the electrochromic phenomenon. Furthermore, practical problems need to be overcome, such as long term degradation and sensitivity to environmental conditions [2-4]. In large area devices, non-uniform coloration-bleaching and the relatively large coloration times need to be dealt with.

The use of electrochromic (EC) windows can contribute to the reduction of the electricity demand for cooling during the summer and heating during the winter and to the reduction of the greenhouse gas emissions. Studies on the use of EC windows in buildings worldwide have shown a range in energy gains depending on window orientation and geographic location of the building. The performance of EC windows can be optimized using control strategy scenarios for the EC use, varying the time that the EC is maintained in the coloured and the bleached state. The maximum possible energy efficiency of EC windows is still under intensive research, both in laboratory conditions and computer simulations [5-6]. Granqvist in [7] reported typical values for annual energy savings of an EC window (maintained annually equally at the coloured and the bleached state) in the range 150-340 kWh per m^2 of glass per year. Using a mixed daylight control strategy, Sullivan et al. [8] simulated EC windows and reported total saving values of 191 kWh/m^2 glass per year.

Our laboratory has been active in the fields of electrochromics and low emittance coatings for more than a decade, aiming to develop materials suitable for energy saving applications in buildings and advanced-glazing. In our earlier works we have used various preparation techniques to prepare EC devices, based mainly on WO_3 thin films with satisfactory stability and performance [9-16].

We have also fabricated devices with V_2O_5 ion storage layers, and multilayer Ag based low emittance coatings that can also be used as transparent conductors [11,17-19].

In this paper, we present the development of EC glazing prototypes with dimensions up to 40 cm × 40 cm. The performance characteristics of the prototypes that have been developed are presented and compared to that of equivalent products. In addition, we determine the total energy savings, the corresponding CO_2 emissions reduction and the avoided human toxic emissions of EC devices application in Greece. For this purpose, the Life Cycle Assessment (LCA) methodology was implemented and the total energy savings of the EC device, the CO_2 emissions reduction and the avoided human toxicity have been calculated assuming the expected lifetime of operation. Finally, the pay back times (PBT) required to compensate the energy, the CO_2 emissions and the toxic emissions of the EC device lifecycle have also been estimated.

2. Experimental Details

2.1. Fabrication of the Prototypes. We have developed and constructed various EC devices. A typical electrochromic prototype is shown in Fig. 1 and comprises of: K-Glass™ / WO_3 / electrolyte / ion storage ($Li_yV_2O_5$) or protective layer (MgF_2) / K-Glass™. The speed of coloration and bleaching of an EC device is governed by the mobility of the metal ions intercalated into the electrochromic layer. For the devices studied in this paper a gel (polymer) electrolyte supplies Lithium (Li^+) ions, which intercalate into tungsten oxide (WO_3) when the appropriate external voltage is applied. This diffusion process of Li ions within the WO_3 matrix depends on the oxide structure. High degree of disorder, large pores and other extended defects increase the rate of Li^+ intercalation. Electron beam evaporated WO_3 films deposited on substrates at room temperature are amorphous, with a columnar morphology [1,11]. These characteristics make them suitable for application in EC devices. The thickness of the WO_3 and MgF_2 (or $Li_yV_2O_5$) thin films was 350 nm and 150 nm respectively, while the electrolyte layer in the 40 cm × 40 cm prototype was 0.8 mm thick.

The WO_3 thin films were deposited on Pilkington K-Glass™ samples, used as the transparent conductor substrates for the prototypes. The samples were thoroughly cleaned before the thin film deposition. A CE certified infrastructure was used for pre-cleaning, while distilled water and chemicals were used for the final cleaning.

The thin films for the fabrication of the electrochromic prototypes were deposited in a specially designed vacuum chamber capable of preparing samples with dimensions up to 40 cm × 40 cm. It consists of a stainless steel chamber measuring 60 cm diameter × 90 cm height, fitted with a multi-pocket electron gun, motorised rotating substrate feedthrough and an in-situ thickness monitor. All the necessary vacuum components for the operation of the system (pumps, feedthroughs, valves, pressure gauges, fittings, control units, etc) have also been installed. The chamber design ensured a ±10 % variation in thickness across the 40 cm × 40 cm samples, which proved to be adequate to prevent noticeable colour deviations. In this chamber, more than one layer could be fabricated without interrupting the procedure, thus allowing multilayer coatings suitable for transparent conductors to be prepared. The deposition parameters and the thickness of the films were monitored in-situ in order to achieve the desired properties. Some of the above mentioned parameters (e.g. film thickness, substrate cleaning, substrate temperature) were found to seriously affect the quality of the produced samples. An optimisation of these parameters was done taking into account the prototype testing results.

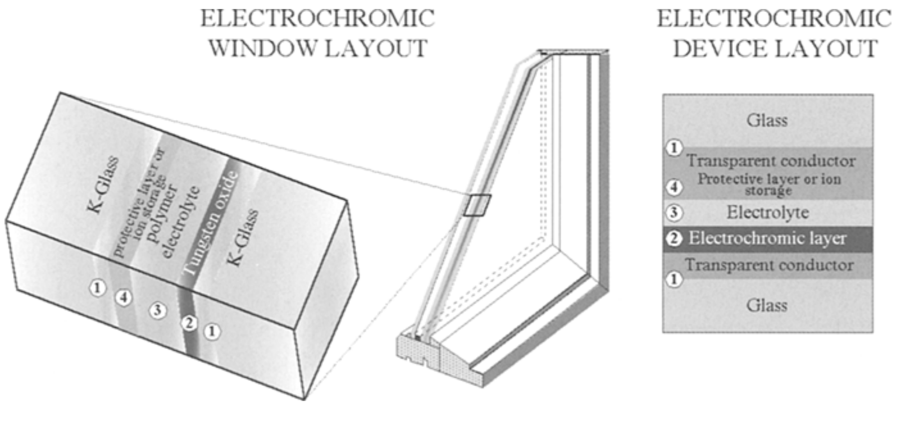


Fig. 1. Electrochromic device layers and electrochromic window layout.

For the fabrication of the electrochromic devices the following procedure was followed: the two halves comprising the electrochromic part of the window (K-

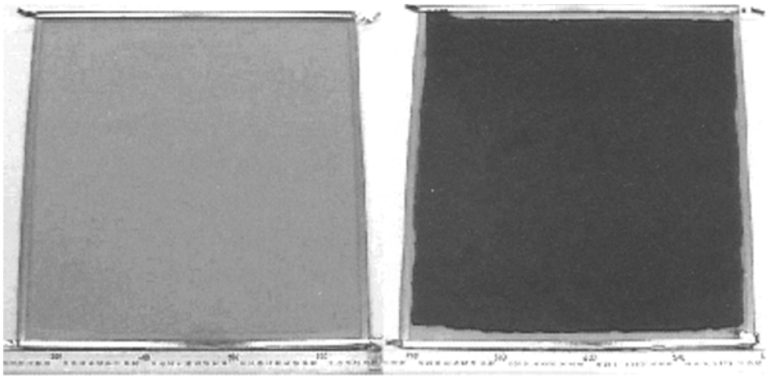
Glass™/WO_3 and MgF_2 (or $Li_yV_2O_5$)/K-Glass™) were joined together by use of silicone glue. The cavity was filled with the electrolyte, which was in-serted through a small entry point. The edges were afterwards sealed peripherally with special epoxy. Then the device was sealed, tested for leakage and it was fully functional. For the fabrication of 3-glass prototypes, the 40 cm × 40 cm K-Glass™/WO_3 part of the electrochromic window was glued on the outer part of an Insulating Glass Unit (IGU) component, which had the transparent conductive coating site on its outer surface.

2.2. Electrochromic Properties of the Prototypes. Many prototypes were prepared and fully tested in many ways. The samples were coloured galvanostatically, with the application of a constant current pulse, and the colour intensity was regulated by the current pulse duration time. The inserted charge during each coloration cycle was 4.6 mC/cm^2. In photos 1 and 2, a typical prototype is being shown in the as-prepared and the fully coloured state. The luminous transmittance of the prototype decreased from 0.63 to 0.02 in the coloured state, giving a Contrast Ratio value of 32:1. The device could be fully bleached by reversing the polarity of the applied current pulses. The coloration efficiency (CE) of the prototype at 550 nm and 650 nm was: CE_{550} = 50.2 cm^2/C and CE_{650} = 92.3 cm^2/C, respectively.

2.3. Testing of the Prototypes for Cycling Durability. The evaluation of lifetime expectancy for the electrochromic devices was carried out via accelerated cycling reversibility experiments. During these tests the electrochromic device was continuously cycled between its fully coloured and fully bleached state in order to achieve the desired number of cycles. Various degradation factors can be set and monitored, such as: decrease of the Contrast Ratio, evolution of non-responsive areas, delamination of layers, etc. Typical electrochromic devices were subjected to cycling reversibility experiments in order to evaluate the effect of continuous coloration/bleaching to their performance.

Cycling reversibility of EC prototypes was evaluated by potentiostatic methods. Deep cycling scenarios (cycling from fully coloured to fully bleached state) have been selected, aiming to test the prototype's capabilities and to bring forward possible defects due to severe or extended use. Various coloration/bleaching scenarios have been evaluated in order to choose the most appropriate aiming to achieve rapid coloration-bleaching and to preserve the life of the devices.

The K-Glass™/WO_3/electrolyte/K-Glass™ devices presented problems during bleaching due to the insertion of Li ions in the plain K-Glass™. Such devices were found to degrade after 1000-2000 deep cycles. To overcome this problem an additional MgF_2 protective layer has been used. K-Glass™/WO_3/electrolyte/MgF_2/K-Glass™ devices have been fabricated and tested. They were found to withstand more than 5000 cycles, which corresponds to a period of 8-12 years of operation for a commercial office building. It was also observed that during continuous cycling the amount of charge flowing through the device was reduced, due to trapping of Li ions into the WO_3 film. The trapped Li ions seem to return to the electrolyte during relaxation intervals. In real working conditions, EC devices will not be subjected to continuous cycling, but to rather short coloration periods followed by large relaxation intervals. Therefore our results for the maximum number of cycles represent a lower limit. In practice the lifetime of the devices is expected to be longer.



Photos 1&2. Electrochromic prototype in the as-prepared and the coloured state.

2.4. Comparison with Equivalent Products. In recent years many laboratories and industrial companies worldwide have fabricated and tested electrochromic devices suitable for glazing applications. Indeed, during the period 1998-2004, 40 such devices have been presented in the literature [2] having the following properties:

1. Dimensions: the electrochromic devices presented in the literature have active areas varying from 2 cm^2 to 4800 cm^2. However, of the 40 devices reported only 5 exceed 100 cm^2 and of them, only 3 exceed 1000 cm^2. The prototypes presen-ted here have area equal to1600 cm^2.

2. Cycling Times: the time required for coloration or bleaching of the devices depends on their dimensions. For large devices (area >1000 cm^2), cycling times exceed 200 s. The prototypes presented here have can be fully coloured in about 100 s.

3. Cycling Durability: it also varies from a few hundred cycles (in the case of most sol-gel devices) to 3×10^5 cycles for sputtered or e-gun deposited films. Degradation of the devices is gradual and propagates around defects, pin holes etc. It is therefore very important for the devices to be defect-free and substrates to be thoroughly cleaned prior to film deposition. The device degradation has been attributed to environmental exposure (UV radiation, thermal stress) and to interaction with the atmosphere (photo-induced degradation in the presence of atmospheric oxygen, moisture ingress, etc). The most durable devices have been cycled at low contrast ratios probably to prolong their life. The prototypes presented here have withstand more than 5000 deep cycles, which corresponds to a period of 8-12 years of operation for a commercial office building.

4. Optical Properties: of the 40 devices reviewed, 15 exhibit a Tlum value that exceeds 70% in the bleached state. In the coloured state, only 8 devices present Tlum lower than 10%. The contrast ratio of the vast majority of the devices is about 5:1 or less, and only 2 of them exceed 10:1. The prototypes presented here have a contrast ratio of 32:1 with Tlum ranging from 63% to 2%.

From the above follows that the fabricated prototypes compare favourably with the state-of-the-art electrochromics (as presented above), with regard to optical properties, coloration times, size and durability.

3. Environmental Efficiency of an Electrochromic Window

3.1. LCA Methodology. In order to estimate the environmental efficiency of an EC window, the Life Cycle Assessment (LCA) methodology was implemented according to the ISO 14040 guidelines. Four phases have been distinguished: Goal and scope definition, Inventory analysis (LCI), Impact assessment (LCIA) and Interpretation [20]. The goal and scope definition of an LCA provides a description of the product system in terms of the system boundaries and a functional unit. The functional unit is the important basis that enables alternative goods, or services, to be compared and analysed. The processes within the life cycle and the associated material and energy flows as well as other exchanges are modelled to represent the product system and its total inputs and outputs from and to the natural environment, respectively. The above procedures result to a model of the product system and to an inventory analysis of environmental exchanges related to the functional unit [21].

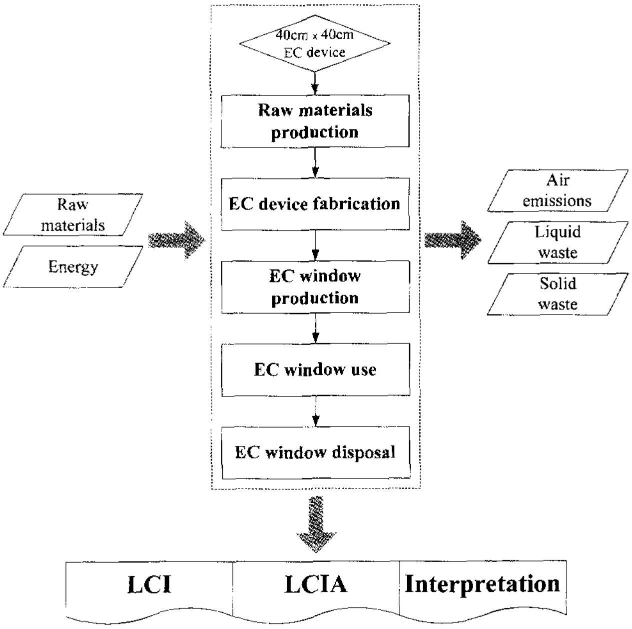


Fig. 2. System boundaries for the electrochromic device life cycle.

Life cycle inventory (LCI) is a methodology for estimating the consumption of resources, the quantities of waste flows and emissions that are attributable to a product's life cycle. In LCI, an integrated analysis of the lifecycle of the device is carried out in order to quantify all inputs used (raw materials and energy) and outputs produced (air, liquid and solid emissions) during the life cycle of the device. Detailed analysis for the production processes of the main constituents of the EC device is carried out. For the phase of the utilisation of the device, the energy savings and the energy consumed for the device operation are calculated simulating a representative scenario of use in Greece.

Life cycle impact assessment (LCIA) provides indicators and the basis for analysing the potential contributions of the resource extractions and wastes/ emissions of the inventory analysis to a number of potential impacts [22]. The result of the LCIA is an evaluation of a product life cycle, on a functional unit basis, in terms of several impact categories (such as climate change, toxicological stress, eutrophication, etc.). Given that this study refers only to greenhouse gas (GHG) emissions and human toxic emissions, the LCIA presented here is restricted to the calculation of the Global Warming Potential and Human Toxicity Potential [23]. The contributing outputs are aggregated through characterisation and classification so that the equivalent CO_2 emissions and 1,4-DCB emissions are calculated, respectively.

3.2. Inventory Analysis. The system boundaries of the LCA study (see Fig. 2) include the following phases: production of raw materials, production of the EC device components, device assembling and EC device use. Device disposal and transportation are not considered in this analysis. Since the system boundaries include the raw materials production processes, we estimate the inputs and outputs for resource extraction and mining processes, procurement of auxiliary materials and all manufacturing processes for each material used [24]. The life cycle inventory analysis includes energy analysis and mass analysis (raw materials input and emissions output) [25].

For the phase of use, the simulation package RESFEN 3.1 [26] was used to compare the energy performance of the EC device with a single clear glass (SG) both assumed to be mounted on an aluminum frame. The simulated EC window consists of an outer pane of clear glazing with an electrochromic layer on the number 2 surface while the inner pane is a conventional high transmittance low-e glazing [8]. All the cooling energy loads were supposed to be generated by electricity, while for the heating loads natural gas is exclusively used. Keeping the single glass as a reference case, the energy savings derived from various control strategy scenarios of the EC have been estimated, for the three climatic zones in Greece (cooling, heating and moderate) [25]. By maintaining the EC glazing mostly in its bleached/coloured state during the cold/hot season, the energy savings have been calculated per EC unit for 25 years of operation. In cooling dominated areas where the most beneficial implementation of the EC glazing is observed, the reduction of cooling and heating loads can reach 127.1 kWh/m^2 glass per year and 94.3 MJ/m^2 glass per year respectively. On the other hand, the energy required for the operation of the EC unit for this lifetime is only about 3.3 MJ.

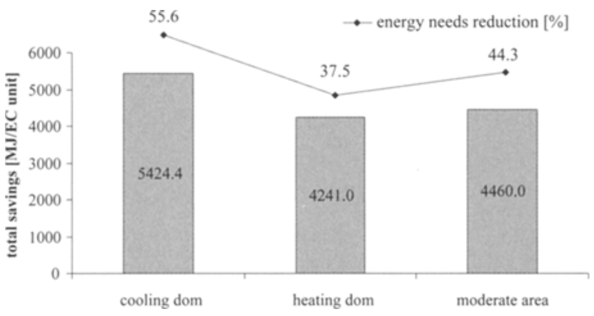


Fig. 3. Net energy efficiency of the EC device.

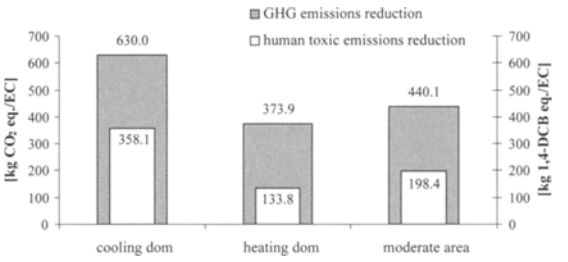


Fig. 4. Net air emissions reduction during the life cycle of the EC device.

3.3. Life Cycle Impacts Assessment. The LCIA analysis was performed according to the operation LCA guide published by the CML [23] using the energy related data (electricity and natural gas) from ETH-ESU data base [27]. The inventory emissions of K-Glass, PC and PMMA are considered for the calculation of the global warming emissions due to raw materials, since they represent the 99% of the device mass [24]. The contribution of the cooling and heating energy systems to the impact categories expressed in equivalent emissions per kWh and MJ respectively have been used [27]. Thus, the electricity required for the device fabrication and its operation during the 25 years lifetime are transformed to category indicators. The total contribution of the life cycle of the EC device to global warming and human toxicity is 13 kg CO_2 and 4 kg 1,4-DCB equivalent, respectively.

On the other hand, the energy savings due to the utilisation of the EC glazing in a building for the expected lifetime, contribute to reduction of these emissions: the cooling savings provide the electricity-avoided emissions, while the avoided natural gas emissions are obtained from the heating savings.

3.4. Analysis of EC Window Environmental Efficiency. The total energy input during the life cycle of the EC device is 183.6 MJ, 98.2% of which is allocated to its production (40% to the embodied energy of raw materials and the rest to fabrication), while only 1.8% allocated to its operation assuming a maximum expected life time of 25 years. Considering the savings derived from the implementation of the EC device in buildings located in the three climatic zones, the total energy input represents

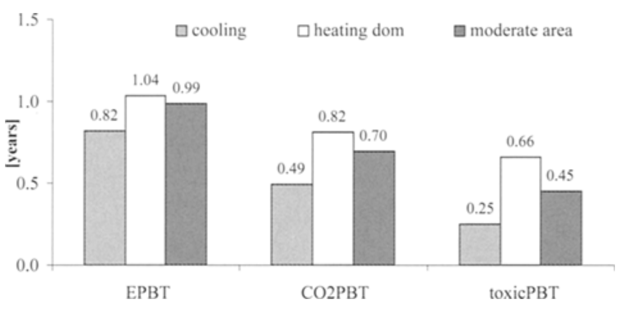


Fig. 5. Energy, CO_2 and toxic PBTs for the EC device.

only 3.3-4.2% of the energy saved. The net energy gains during its lifecycle, i.e. the total avoided energy consumption are presented in Fig. 3. The beneficial use of EC devices in cooling dominated areas is obvious, providing savings that reduce the building energy needs more than 55%.

According to LCIA analysis it was found that 13 kg CO_2 equivalent are emitted during the EC device lifecycle. Reduction of GHG emissions due to cooling and heating savings range between to 387 and 643 kg CO_2 equivalent in heating and cooling dominated areas respectively. Consequently, net CO_2 emissions reduction can reach up to 630 kg CO_2 equivalent in cooling dominated areas (see Fig. 4). The significance of these avoided emissions can be obvious when we take into account that they correspond to the equivalent CO_2 emitted corresponding to the use of 520 kWh electricity.

Human toxic emissions are 4 kg 1,4-DCB equivalent emitted during the EC device lifecycle. The emission of the range 138-362 kg 1,4-DCB equivalent is avoided due to cooling and heating savings in the 25 years lifetime. Thus, the net human toxic emissions reduction is equal to 358 kg 1,4-DCB equivalent for cooling dominated regions (see Figure 4). This corresponds to the equivalent 1,4-DCB emitted due to the use of 510 kWh electricity.

The Energy PBT, the CO_2 PBT and the toxicPBT are presented in Fig. 5 for the three climatic regions considered. In all cases the time required to compensate the energy input or the emissions attributed to the device lifecycle doesn't exceed the duration of one year. Indeed, after 0.8-1 years of operation the input energy from its whole lifecycle is saved and the rest of its lifetime is an energy-saving device. Furthermore, only 0.5-0.8 years of operation are required to compensate the lifecycle CO_2 emissions and even lower (0.25-0.7 years) for the toxic emissions.

4. Conclusions

Electrochromic devices with dimensions up to 40 cm × 40 cm were fabricated in a vacuum chamber designed and built for this purpose. They exhibit favorable optical characteristics, cycling reversibility and durability. Electrochromic glazing prototypes have been prepared attaching a 40 cm × 40 cm WO_3 coated glass on an insulated glass unit (3 glass arrangement). The devices exhibit excellent optical performance, with contrast ratio up to 1:32 (visible dynamic transmittance range $T_{lum,bleached} = 63\%$ and $T_{lum,colored} = 2\%$), and coloration efficiency up to 92 cm^2/C. The prototypes were tested for durability and performance and were found to compare favourably with state-of-the-art electrochromic devices and other equivalent products.

EC devices can replace conventional glazing by reducing the energy consumed during a building's lifetime. The scenarios of an improved control strategy for the use of electrochromic devices in a building have proved their energy benefits and their environmental benign behaviour. The importance of maximising the energy savings should be assessed according to the corresponding maximisation of the avoided emissions to the environment. This concerns mainly the GHG emissions, measured as equivalent kg of CO_2, since they are the major impact category to which the energy production facilities contribute.

Considering the Greek climatic conditions, we investigated a control strategy by which the EC glazing is maintained mainly at the coloured/bleached state during the hot/cold season throughout the year respectively. We estimated that the energy input during the device lifecycle doesn't exceed 4% of the energy saved assuming 25 years of operation. In cooling dominated areas we can obtain the best performance of the EC glazing, with reduction of building energy requirement up to 55.7% compared with a single glass. That corresponds to cooling and heating savings of 127.1 kWh/m^2 glass per year and 94.3 MJ/m^2 glass per year respectively. The lifecycle contribution to the reduction of GHG emissions is measured as net CO_2 emissions reduction that is equivalent to 630 kg CO_2/EC unit. As far as the reduction of human toxic emissions is concerned, the EC glazing corresponds to net human toxic emissions reduction equivalent to 358 kg 1,4-DCB.

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6. References

[1] C.G. Granqvist, Handbook of inorganic electrochromic materials, Amsterdam, Elsevier, 1995.

[2] C.G. Granqvist, E. Avendaño and A. Azens. Electrochromic coatings and devices: survey of some recent advances. Thin Solid Films **442** **(1-2)**, 201-211 (2003).

[3] A.W. Czanderna, C.M. Lampert, Evaluation criteria and test methods for electrochromic windows. SERI/TP-255-3537, Solar Energy Research Institute, 1990.

[4] N. Sbar, M. Badding, R. Budziak, K. Cortez, L. Laby, L. Michalski, T. Ngo, S. Schultz, K. Urbanik, Progress toward durable, cost effective electrochromic window glazings. Solar Energy Materials and Solar Cells **56**, 1999, 321-341.

[5] S.E. Selkowitz, M. Rubin, E.S. Lee and R. Sullivan, A review of electrochromic window performance factors. Lawrence Berkeley Laboratory, LBNL 35486, UC 1600, 1994.

[6] J. Karlsson and A. Roos, Annual energy window performance versus glazing thermal emittance -.the relevance of very low emittance values. Thin Solid Films **392** (**2**), 345-348 (2001).

[7] C.G. Granqvist, Charge your glasses with electrochromic glazing. International Glass Review **2**, 67-68 (2001).

[8] M. Sullivan, M. Rubin and S. Selkowitz, Energy performance analysis of prototype electrochromic windows. Lawrence Berkeley Laboratory, LBNL 39905, 1996.

[9] S. Papaefthimiou, G. Leftheriotis and P. Yianoulis, Electrochromic Phenomena in Transition Metal Oxide Thin Films Prepared by Thermal Evaporation. Ionics **4**, 321 (1998).

[10] S. Papaefthimiou, G. Leftheriotis and P. Yianoulis, Study of WO_3 films with textured surfaces for improved electrochromic performance. Solid State Ionics **139**, 135-144 (2001).

[11] S. Papaefthimiou, G. Leftheriotis and P. Yianoulis, Advanced electrochromic devices based on WO_3 thin films. Electrochimica Acta **46** **(13-14)**, 2145-2150 (2001).

[12] G. Leftheriotis, S. Papaefthimiou, P. Yianoulis and A. Siokou, Effect of the tungsten oxidation states in the thermal coloration and bleaching of amorphous WO_3 films. Thin Solid Films **384**, 298-306 (2001).

[13] G. Leftheriotis, S. Papaefthimiou, P. Yianoulis, A. Siokou and D. Kefalas, Structural and electrochemical properties of opaque sol-gel deposited WO_3 layers. Applied Surface Science **218**, 275-280 (2003).

[14] G. Leftheriotis, S. Papaefthimiou and P. Yianoulis, The effect of water on the electrochromic properties of WO_3 films prepared by vacuum and chemical methods. Solar Energy Materials & Solar Cells **83**, 115-124 (2004).

[15] A. Siokou, G. Leftheriotis, S. Papaefthimiou and P. Yianoulis, Effect of the tungsten and molybdenum oxidation states on the thermal coloration of amorphous WO_3 and MoO_3 films. Surface Science **482-485**, 294-299 (2001).

[16] A. Siokou, S. Ntais, S. Papaefthimiou, G. Leftheriotis and P. Yianoulis, Influence of the substrate on the electrochromic characteristics of lithiated α-WO_3 layers. Surface Science **566–568**, 1168-1173 (2004).

[17] S. Papaefthimiou, G. Leftheriotis and P. Yianoulis, Study of electrochromic cells incorporating WO_3, MoO_3, WO_3-MoO_3 and V_2O_5 coatings. Thin Solid Films **343-344**, 183-186 (1999).

[18] G. Leftheriotis, S. Papaefthimiou and P. Yianoulis, Integrated low-emittance-electrochromic devices incorporating ZnS/Ag/ZnS coatings as transparent conductors. Solar Energy Materials & Solar Cells **61**, 107-112 (2000).

[19] G. Leftheriotis, S. Papaefthimiou and P. Yianoulis, Development of multilayer transparent conductive coatings. Solid State Ionics **136-137**, 655-661 (2000).

[20] ISO 14040. Environmental management-Life cycle assessment-Principles and framework. The International Organisation for Standardisation, 1997.

[21] G. Rebitzer, T. Ekvall, R. Frischknecht, D. Hunkeler, G. Norris, T. Rydberg, W.P. Schmidt, S. Suh, B.P. Weidema and D.W. Pennington, Life cycle assessment Part 1: Framework, goal and scope definition, inventory analysis and applications. Environment International **30(5)**, 701-720 (2004).

[22] D.W. Pennington, J. Potting, G. Finnveden, E. Lindeijer, O. Jolliet, T. Rydberg and G. Rebitzer, Life cycle assessment Part 2: Current impact assessment practice. Environment International **30(5)**, 721-739 (2004).

[23] Leiden University, Life Cycle Assessment: An operational guide to ISO standards. Centre of Environmental Science, Leiden University, 2001, The Netherlands.

[24] E. Syrrakou, S. Papaefthimiou and P. Yianoulis, Environmental assessment of advanced glazing. Solar Energy Materials and Solar Cells **85(2)**, 205-240 (2005).

[25] S. Papaefthimiou, E. Syrrakou and P. Yianoulis, Energy performance assessment of an electrochromic window. Accepted for publication in Thin Solid Films 2005.

[26] LBNL, Lawrence Berkeley National Laboratory: RESFEN 3.1. LBNL-40682 Rev. BS-371 Berkeley, CA 94720 USA, 1999.

[27] SimaPro 6, Pre Consultants, Netherlands 2005, www.pre.nl.

Paper presented at the Patras Conference on Solid State Ionics - Transport Properties, Patras, Greece, Sept. 14 - 18, 2004.

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