IOP Conference Series: Earth and Environmental Science

PAPER • OPEN ACCESS

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To cite this article: D Mann *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1085** 012060

IOP Conf. Series: Earth and Environmental Science 1085 (2022) 012060 doi:10.1088/1755-1315/1085/1/012060

SunSmart – The First Affordable, Energy Optimized Smart Window

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Abstract. Reducing energy consumption and CO_2 emissions becomes more and more important. Not only because of climate change related issues, but also to realize our ambition to become energy independent. To increase the energy-efficiency in buildings, we developed a thermochromic coating for smart windows which is optimized for climates with seasonal changes. Here we present the first results of our smart window performing in real environment. We show that measured solar transmission and thermochromic performance is comparable to measurements in the lab. Furthermore, we present a further optimized thermochromic coating with record optical properties of T_{vis} = 70% and ΔT_{sol} = 20.1%. Via a building energy simulation study using data from this high performing coating, we show that energy savings between 17-37% can be achieved in the Netherlands, depending on the building type. Furthermore we show that by the use of our new smart window annual energy cost savings between 266 – 553 EUR/a for a single household can be achieved. The thermochromic coating usually accounts for 60 – 70% of these cost savings equaling between 8 – 10 EUR/a per m^2 glass. Due to the low material and processing costs for the thermochromic coating, an attractive return on invest with market conform profit margin is possible.

1. Introduction

Reducing energy consumption and CO_2 emissions becomes more and more important. Not only because of climate change related issues, but also to realize our ambition to become energy independent. In Europe, more than one third of our total energy consumption and CO_2 emission result from the building sector with more than 50% of this energy being used for Heating, Ventilation and Air-Conditioning (HVAC) systems [1]. Here, windows account for more than 30% of the total energy consumption in buildings, mainly due to heat loss through windows in winter and unwanted solar heat gain in summer [2]. In current newly raised buildings state-of-the-art energy-efficient windows are being used to improve energy-efficiency and reduce energy consumption. Nevertheless, the European building stock is still mostly equipped with dated, inefficient glazing. A recent study, commissioned by Glass for Europe, analyzing the energy and CO_2 emission savings potential, has shown that by equipping all buildings in Europe with energy-efficient glazing, the total energy consumption of the building sector can be reduced by over 30% for most countries in Europe. That means, if this transition were completed in the whole European Union, by 2030 annual energy saving of 75.5 Mt oil equivalents (with 1 kt of oil equivalent equals 11.6 GWh) and annual emission reduction of 94.5 Mt CO_2 would be achieved [3,4]. There is a huge potential for energy savings and emission reduction via introduction of state-of-the-art energy-efficient windows, but also via development of new materials and technologies that show even better performance.

State-of-the-art energy-efficient windows are either designed to reduce radiator heat loss or for solar control, blocking as much solar heat as possible with minimum impact on visible transmission. Due to their static optical properties, they are most efficient in climates that don't vary. When requirements for a window change due to seasonal changes in e.g. continental climate, these windows fall short, since they cannot adapt to these changing requirements. New developments are focusing on adaptive systems, such as thermochromics [5], which can switch their solar heat gain properties depending on the building's needs. Hereby solar heat can be used in a building when needed and blocked from entering when it's not desired, enabling optimum solar heat management.

2. Technology

Thermochromics can switch their IR modulating properties from transmissive to blocking depending on the glazing temperature [5]. Recently we have published several reports on our SunSmart, thermochromic window development [6-8]. The single layer coating, we developed, uses vanadium dioxide (VO_2) as thermochromic material, which changes its crystal structure and hereby infrared transmission at a specific temperature. The transition temperature of 68°C for pure VO_2 crystals can be adjusted to application oriented temperatures around 20°C using metal ion doping [5,9]. By using a mixture of VO_2 in a silicon dioxide matrix, we realized unrivaled optical properties, combining high visible transmission (T_{vis}) with high solar modulations (ΔT_{sol}). In the study we showed that both values can be adjusted via VO_2 content and layer thickness and that combined values of T_{vis} > 60% and ΔT_{sol} > 10% can be reached [6, 10]. Furthermore, we reported on building energy simulation studies, analyzing the performance of our smart window technology in various climate regions [7] and in different building types common in the Netherlands [8]. We showed that our smart window is optimized for climates with changing seasons, outperforming state-of-the-art solutions, and that energy savings of up to 30% can be reached in the Netherlands, depending on the building type. Here we report first results from a thermochromic window demonstrator installed in a test building in Eindhoven and measured in real environment. Furthermore, we report further improved optical properties of thermochromic coatings reaching record values of T_{vis} = 70% and ΔT_{sol} > 20% and respective impact on energy savings in various Dutch buildings, i.e. stand-alone, duplex, terraced and apartment buildings, via building energy simulations. In addition, we give a brief overview over material and processing costs, showing the enormous market potential for this new type of window.

3. Pilot testing

dIn addition to the thermochromic material as coating, we have developed thermochromic pigments containing VO_2 in <100 nm sized particles. These pigments can be integrated into a coating matrix or a polymer film to add thermochromic properties to a range of window products. Using these pigments, with an adjusted transition temperature to 26°C via tungsten doping, we have prepared thermochromic PVB films at 760 μm thickness for lamination of safety glass. These films were used to prepare 1x1 m^2 window demonstrators via lamination and assembling into an insulated glazing unit (IGU) to be tested in real environment (Figure 1a). The windows were installed at the SolarBEAT test facilities in Eindhoven in addition to regular clear IGUs as reference and mounted spectrophotometers behind both thermochromic and reference IGU for investigation of visible and infrared transmission (Figure 1b). Two sensors acquired data in wavelength regions between 350 – 900 nm and 900 – 1700 nm, respectively. In the first warm days in March 2022, a drop in infrared transmission was observed for the thermochromic window in the early afternoon. To investigate this observation in detail, expected transmission spectra for the thermochromic IGU in the cold and hot state as well as for the reference IGU were calculated using spectral data acquired using a UV-vis-NIR spectrophotometer in the lab and

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the AM1.5 spectrum [11] (Figure 2a). These spectra were compared to acquired spectra from the sensors at SolarBEAT measuring solar transmission between 900 – 1700 nm in real environment on March 10th 2022. To investigate the transmission spectra before and after the observed drop in infrared transmission, two acquired data sets were chosen, one in the late morning (11:00; Figure 2b) and one in the early afternoon (15:00; Figure 2c), and the acquired transmission data was compared to the calculated spectra from lab measurements. Furthermore, the light transmission at 1000 nm was compared between the thermochromic and the reference IGU by calculating the ration *r = T(1000 nm; ref) / T(1000 nm; demo)*. A good match between measured and expected spectra was observed both for the reference IGU as well as for the thermochromic IGU. Furthermore, the acquired spectrum of the thermochromic IGU in the late morning matched well with the expected spectrum for the cold state and the spectrum acquired in the early afternoon matched well with the expected spectrum for the hot state, confirming the observation of thermochromic switch in real environment. To investigate the overall performance of the real life demonstrator with the expected performance measured in the lab, we compared the transmission ratios at 1000 nm for cold and hot state with acquired data. The ratio between reference IGU and thermochromic IGU transmission in the late morning was 75%, whereas the expected ratio was calculated to be at 80%. Here a good fit between measured and expected ratio was obtained and the slight discrepancy can be explained by the thermochromic material in the IGU having already partly switched to the infrared blocking state. For the early afternoon a ratio between thermochromic and reference IGU of 66% was measured. This compares well to the expected ratio of 68% calculated from lab data. Overall the thermochromic performance measured in real environment matches well with expected performance calculated from lab data.

a)  b) 

Figure 1. a) 1x1 m^2 laminated glass with thermochromic PVB interlayer. b) Thermochromic IGU installed in SolarBEAT test facilities.

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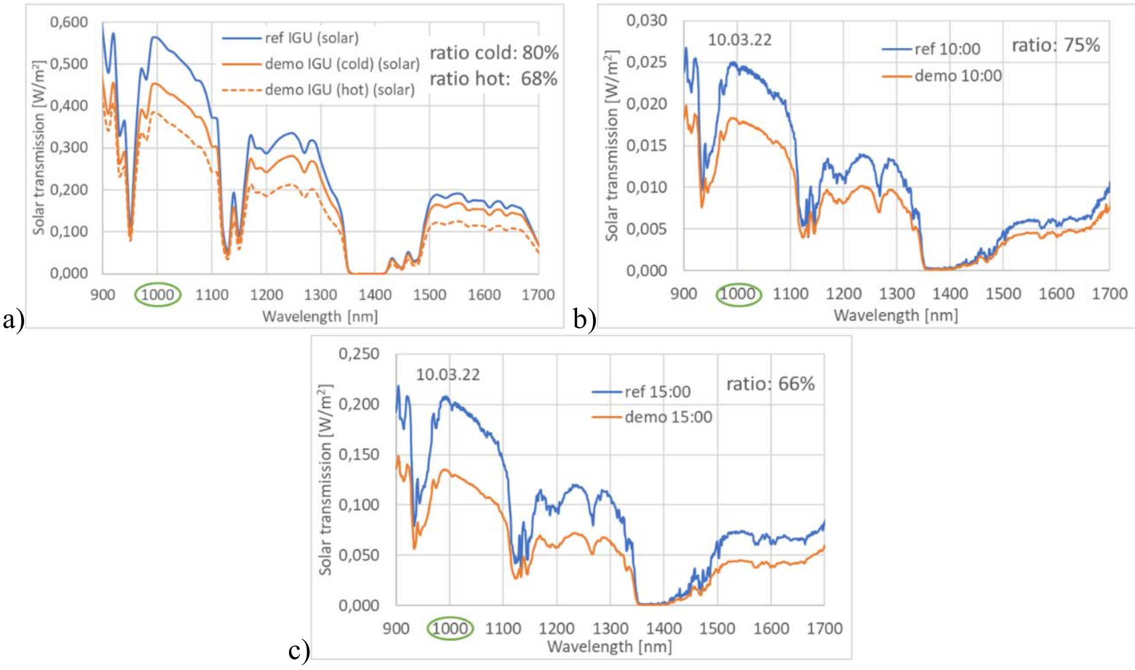

Figure 2. a) Expected infrared transmission of reference (blue) and thermochromic (demo) IGU in cold (orange, full line) and hot (orange; dotted) state calculated from lab measurements and AM1.5 spectrum. Measured transmission through reference (blue) and thermochromic (demo; orange) IGU at 10:00 (b) and 15:00 (c) at SolarBEAT in Eindhoven.

In addition to the real environment testing of laminated IGUs, we have further developed our thermochromic coating in the lab. Here, by careful adjustment of reaction parameters, we could realize further improvement of optical properties. Essential to increase the solar modulation >15% was to realize small, evenly distributed VO_2 domains that experience plasmonic properties in the metallic state [12]. These plasmonic properties, that only occur in the metallic state, lead to increased absorption in the wavelength region between 800 – 1300 nm. Since the solar infrared intensity in this region is highest, it has a major impact on the total solar transmission. Using this phenomenon and adjusting VO_2 content and coating thickness for high total solar transmission in the cold state, we could realize a thermochromic coating with T_{vis} of 70% and a ΔT_{sol} of 20.1% (Figure 3). These combined values exceed everything reported in literature to date, including nanocomposite films also making use of the plasmonic properties of nanometer sized VO_2 domains [6].

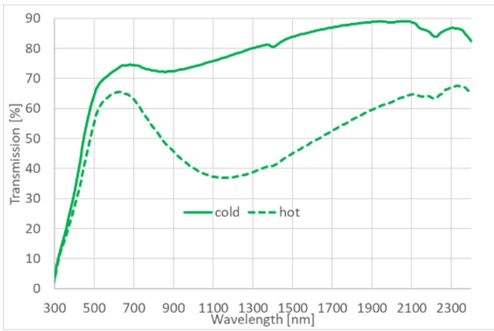

Figure 3. UV-vis-NIR transmission spectrum of thermochromic coating in cold (solid line) and hot (dashed line) state.

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4. Impact analysis

We used the spectral data of this new high performance coating in building energy simulations for four different types of buildings common in the Netherlands. Here we chose a stand-alone building, one unit of a duplex house, one unit of a terrace house and one unit in an apartment building for our study. For this study we used the simulation software Energy Plus version 9.2.0 [11] with parameters detailed in our previous report [7]. As a reference point, we simulated the annual energy consumption of the 4 building units equipped with an IGU made of two clear glass panes (Pilkington Optiwhite) and a 13 mm argon filled gap (clear IGU). The energy demand of these reference buildings were then compared to the simulated annual energy consumption for the same buildings equipped with our thermochromic smart window, which comprised a coated glass with our developed thermochromic coating and a low-e coated glass (Saint-Gobain ECLAZ) in an IGU with also a 13 mm argon filled gap (smart widow). The selected stand-alone building, duplex and terrace house had a similar ratio of m^2 window surface to m^2 living space. The most significant difference between those 3 buildings was the total floor area, decreasing from stand-alone to duplex and terrace house, and the number of walls in contact with the outside environment.

The largest impact of the smart window on annual energy consumption was obtained for the stand-alone building. Here using the smart window, annual energy savings of 22.8% in comparison to the reference stand-alone building equipped with clear IGU could be reached (Figure 4). With reduced floor area and either three or two outside walls being in contact with the environment, for duplex and terrace house respectively, the impact of the smart window on total energy consumption declined in comparison to the clear IGU. Here annual energy savings of 20.0 and 16.7% were achieved for the duplex and terrace house, respectively (Figure 4). The apartment unit was not directly comparable to the other houses, since it is a one floor unit with large window surfaces on the two outside walls in contact with the environment. Here the big window surface area in relation to the total floor area, leads to a big impact of the type of window on annual energy consumption. Therefore, very high annual energy savings of 37.1% could be reached in comparison to the clear IGU (Figure 4).

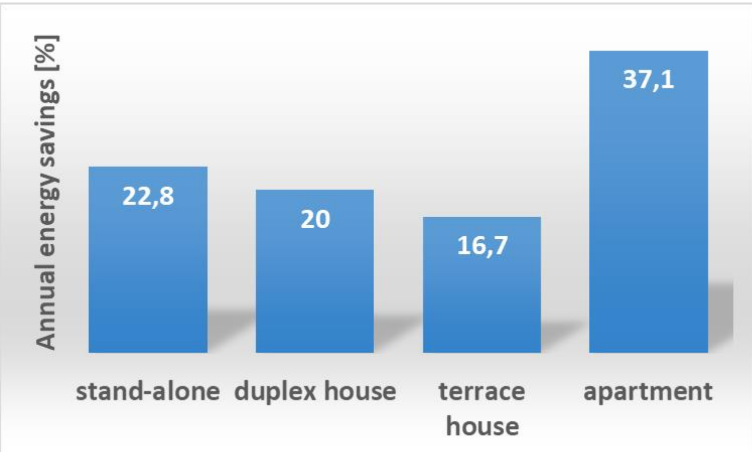

Figure 4. Annual energy savings of different building types in the Netherlands equipped with thermochromic smart window in comparison to the same building equipped with clear IGU.

The total energy consumption and savings simulated in the study are a combination of heating, cooling and lighting contributions. Using this division in combination with the average cost price for gas and electricity in the Netherlands, annual cost savings for each building type can be calculated [7]. Here the annual cost savings are very much dependent on the total energy costs for each building type. Therefor the building type with the highest annual energy savings in %, doesn`t necessarily also have the highest total annual cost savings. The free-standing building with the highest total energy demand also showed the largest annual cost savings of 553 EUR/a for the smart window in comparison to clear IGU (Figure 5). When subtracting the cost savings, which can be attributed to the low-e coating in the smart window, the added annual cost savings per m^2 attributed to the thermochromic coating can be calculated. For the free-standing building, the duplex and the terrace house, the contribution of the thermochromic coating was approximately 60 – 70%, which leads to annual cost savings between 8 – 10 EUR/a per m^2 window. Due to the big impact of the thermochromic smart window on cost savings for the apartment unit, here annual cost savings attributed to the thermochromic coating in the smart window of 21 EUR/a per m^2 window can be achieved, making the new technology very attractive for home owners.

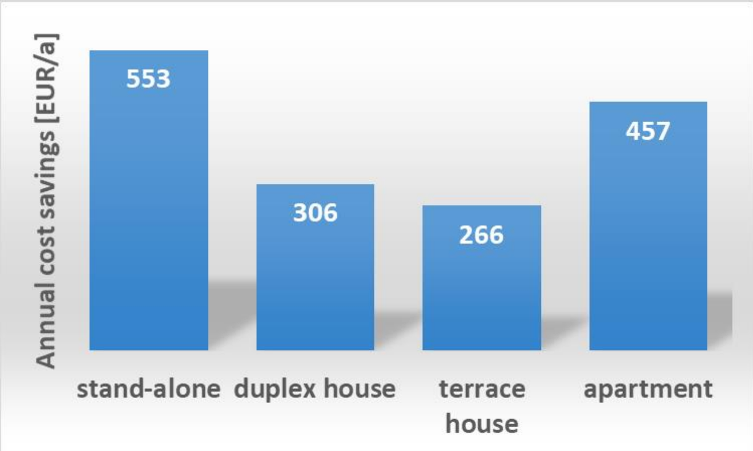

Figure 5. Annual cost savings of different building types in the Netherlands equipped with thermochromic smart window in comparison to the same building equipped with clear IGU.

In addition, we analyzed the cost structure for the new technology. Here we performed a detailed analysis of materials and processing costs, considering both CAPEX and OPEX for the processing equipment. Depending on the factory operations schedule and the amount of production loss, the analysis gave a result of 3 – 5 EUR/m^2 average production costs. Due to the high benefits of the smart window for the end user, even including added costs for e.g. logistics and a market conform profit margin, an attractive return on invest of < 7 years can be achieved.

5. Conclusion

In this report, we showed the first results of our thermochromic smart window in real environment. The measured transmission and thermochromic performance was in good agreement with expected transmission data from the lab and a clear confirmation of the functioning thermochromic effect was obtained. Furthermore, we reported on further optimization of our thermochromic coating to increase T_{vis} and ΔT_{sol} simultaneously to combined record values of 70% and 20.1%, respectively. In addition, we showed, via a simulation study, the impact of our new smart window, leading to potential annual energy savings between 17 – 23% in stand-alone buildings, duplex and terrace houses. We showed that home owners can safe between 8 – 10 EUR/m^2 glass per year due to our thermochromic coated glass and that due to low production costs of 3 – 5 EUR/m^2 an attractive return on invest and market conform profit margin are possible. For apartments units or buildings with large window facades annual energy and cost savings are even higher, reaching up to 37% and 21 EUR/a per m^2 window, respectively.

Acknowledgements
The research work in this paper was carried out within Brightlands Materials Center, a joint research initiative between TNO and the province of Limburg. The work is funded by the Dutch government as well as the province of Limburg. Additionally, the work was partly performed within the Interreg Vlaanderen-Nederland project Sunovate and within the OP Zuid project LEEF.

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