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Building energy simulations for different building types equipped with a high performance thermochromic smart window

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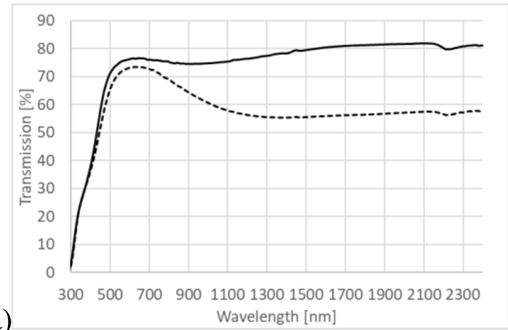
Abstract. With constantly progressing climate change and global warming, we face the challenge to reduce our energy consumption and CO_2 emission. To increase the energy-efficiency in buildings, we developed a thermochromic coating for smart windows which is optimized for intermediate climates. Here we present a building energy simulation study for the use of our smart window in the four main residential building types in the Netherlands. In the study we show that for all building types energy savings between 15-30% can be achieved. Hereby the impact of the windows on energy consumption is dependent on the window surface area as well as the total floor space. Furthermore we show that by the use of our new smart window, where the thermochromic coating is combined with a standard low-e coating, annual cost savings for energy between 220-445 € for a single household can be achieved. The thermochromic coating usually accounts for half of these cost savings, that is an addition in cost savings between 6-7.5 €/m^2 glass. Due to the low material and processing costs for the thermochromic coating, a return on invest within 7 years should be feasible with these annual cost savings.

With constantly progressing climate change and global warming, we face the challenge to reduce our energy consumption and CO_2 emission. 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]. A large part of this energy consumption results from heat loss through windows in cold conditions, or from cooling due to solar heat gain through windows. Therefore, windows account for more than 30% of the total energy consumption in buildings [2]. To improve the energy efficiency of windows and reduce the energy consumption of buildings, there are already several different energy-efficient glazing systems on the market. 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]. This shows the huge energy savings and emission reduction potential of not only the introduction of already available energy-efficient glazing systems, but also of the development of new materials and technologies already outperforming the commercial ones.

Current energy efficient glazing systems are either static infrared (IR) blockers, to reduce the transmission of solar heat into a building, low emissivity glazing, to increase insulation and reduce radiator heat loss through the window or a combination of both. These systems are suited best for either hot climates, where solar heat has to be blocked the whole year, or cold climates, where insulation and reduction of radiator heat loss is desired constantly. Current research and development focuses on adaptive systems, such as thermochromics [5], which can switch their solar heat gain properties depending on the building's needs. These properties are required in intermediate climates with hot summers and cold winters.

Thermochromics can switch their IR modulating properties from transmissive to blocking depending on the glazing temperature [5]. In a recent study we have shown that smart windows, where our thermochromic coating is combined with a standard low-e coating, are perfectly optimized for intermediate regions, where heating and cooling are equally important over the year [6]. In this study we have analyzed a free standing residential building in 10 different climate zones. For intermediate climates energy savings of up to 22% could be achieved with our smart window, outperforming all compared commercial energy-efficient glazing systems. Due to the nature of the study and to be able to compare the impact of the window in different climate regions, the rest of the building envelop was kept constant and not adapted to each location. For a more detailed analysis of the performance of the thermochromic smart widow in the Netherlands, we here present a study on the 4 main building types. In 2015, 23% of homeowners in the Netherlands lived in free-standing buildings, 19.6% were living in duplex houses, 42.5% lived in terrace houses and 15% in apartments [7]. Therefore we chose those 4 building types for a building energy simulation study.

In our labs we have developed a thermochromic coating with excellent optical properties for application in smart windows. The functional material in the coating is VO_2,which changes its crystal structure and therefore its optical properties at 68°C [5]. By use of metal ion doping, the switching temperature can be reduced to temperatures suitable for application, e.g. at 20°C [6,8]. The coating developed in our labs shows high visible transmission (T_{vis}) of 74% combined with a high solar modulation (ΔT_{sol}) of 10% [9] (Figure 1). This combination of high T_{vis} and ΔT_{sol} is unrivaled by thermochromic VO_2 based coating reported in literature to date [10].

a)


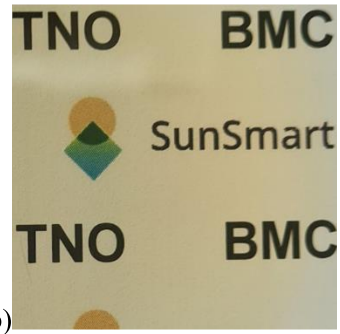
b)


Figure 1. a)UV-vis-NIR transmission spectrum of thermochromic coating in cold (solid line) and hot (dashed line) stae. b) picture of coated glass plate.

For the building energy simulation study we integrated the thermochromic coated glass in an insulating glazing unit (IGU) with a low-e coated glass (Saint-Gobain ECLAZ) and a 13 mm argon filled gap, reaching a U value of 1.1 $W \cdot m^{-2} \cdot K^{-1}$. The selected buildings were designed according to current new building construction projects in the Netherlands found on the internet (Figure 2). For duplex and terrace houses as well as for apartments, one unit was choses instead of the total building complex. For terrace houses one of the central units was chosen. Wall material was selected according to current

Dutch regulations reaching an *Rc* value (thermal resistivity of the composite) of 4.7 $m^2K \cdot W^{-1}$. We used the software Energy Plus version 9.2.0 [11] for the simulations. The selected simulation period was one year with data points gathered monthly. All other parameters were used as reported in our previous building energy simulation study [6].

Figure 2. Selected buildings for building energy simulation study on thermochromic smart window. a) free-standing, b) apartment, c) terrace house and d) duplex house.

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. 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. The selected free-standing 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 and the number of walls in contact with the outside environment. Here the free-standing building with the largest floor area and all 4 outside walls in contact with the environment showed the largest impact of the smart window on annual energy consumption. Here annual energy savings of 21.2% could be reached (Figure 3). With reduced floor area and either three or two outside walls being in contact with the environment, for duplex and terrace building respectively, the impact of the smart window on total energy consumption declined. Here annual energy savings of 16.1 and 15.4% were achieved for the duplex and terrace house, respectively (Figure 3). The apartment was a more special case, 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 thermochromic smart window on annual energy consumption. Here annual energy savings of 29.4% could be reached in comparison to standard IGUs (Figure 3).

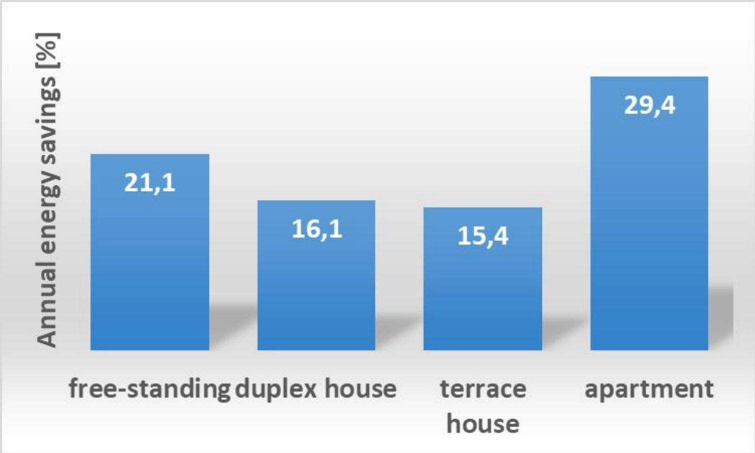


Figure 3. Annual energy savings of different building types in the Netherlands equipped with thermochromic smart windows in comparison to standard clear IGUs.

The simulated energy consumption and savings could be divided into heating, cooling and lighting contributions. Suggesting that natural gas was used for heating and electricity for cooling and lighting, the average cost price for gas and electricity in the Netherlands could be used to calculated annual cost savings for each building type. 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. Here the free-standing building showed with 445 € the largest annual cost savings of all building types (Figure 4), due to the highest total energy demand. When subtracting the cost savings, which can be attributed to the low-e coating in the smart window, the added 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 50%, which leads to annual cost savings between 6-7.5 €/m^2 window. Due to the cheap material and processing cost a return on invest within 7 years will be possible with these attributed cost savings. Due to the big impact of the thermochromic smart window on cost savings for the apartment, here annual cost savings attributed to the thermochromic coating in the smart window of 14.5 €/m^2 window can be achieved, making the new technology very attractive for home owners.

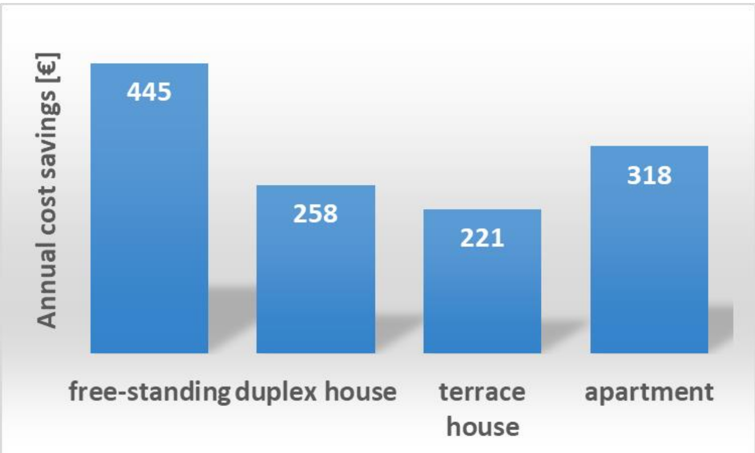


Figure 4. Annual cost savings of different building types in the Netherlands equipped with thermochromic smart windows in comparison to standard clear IGUs.

In this report, we showed the results of a building energy simulation study on the four main building types in the Netherlands. We compared the annual energy savings for use of a thermochromic smart window in a free-standing building, a duplex house, a terrace house and an apartment to standard clear

IGUs. The thermochromic coating developed in our labs shows a combination of high T_{vis} and ΔT_{sol}, which is unrivaled in scientific literature on thermochromic VO_2 based coatings. In our simulation study we could show that the use of a smart window, where our thermochromic coating is combined with a standard low-e coated glass, can lead to annual energy savings between 15-21% in free-standing buildings, duplex and terrace houses. For apartments with large window areas even higher energy savings of up to 30% can be reached. In total the thermochromic coating adds between 6-7.5 €/m^2 in cost savings to standard low-e glass, which is currently used in new built homes. Here due to low additional production costs, a return on invest within 7 years is feasible. For apartments with large window surface areas even higher cost savings are possible, up to 14.5 €/m^2 window.

Acknowledgements

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[9] T_{vis} and ΔT_{sol} are defined as $T_{vis,sol} = \frac{\int \Phi_{vis,sol}(\lambda)T(\lambda)d\lambda}{\int \Phi_{vis,sol}(\lambda)d\lambda}$ and $\Delta T_{sol} = T_{sol,cold} - T_{sol,hot}$, where $T(\lambda)$ is the transmittance at wavelength λ, $\Phi_{vis}(\lambda)$ is the photoscopic spectral sensitivity of human vision, and $\Phi_{sol}(\lambda)$ as the AM 1.5 solar irradiance spectrum.
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