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Transparent facades in low energy office buildings

Numerical simulations and experimental studies

Thesis for the degree of Philosophiae Doctor

Trondheim, May 2015

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PREFACE

To a certain extent, engineers consider windows a necessary evil and see them as energy drains in the building envelope. Architects on the other hand understand the importance of the link windows create between the interior and the exterior of the building fabric. Being a PhD candidate employed at the faculty of Architecture and Fine Arts with a background as an engineer has created a window of opportunity to investigate these contradicting points of view.

This PhD is funded by the Research Centre on Zero Emission Buildings (ZEB Centre), which was established in 2009, and it investigates how windows can be applied in low-energy buildings of today and the future. The main structure of the thesis is based on results from computer simulations and laboratory experiments. The work presented here is centred on quantitative descriptors used to assess the building performance as a function of window configurations.

I would like to thank everyone who has been involved in any way with getting this PhD finished. All my colleagues at the ZEB Centre and at SINTEF Building and Infrastructure need a special mention!

In particular, I would like to thank my two supervisors, Arild Gustavsen and Berit Time. You have been invaluable in helping me to finish this thesis. Thank you for all your good advice, guidance and motivational input along the way. Egil Rognvik deserves a big thanks for helping me with all the experimental work in the lab. I would probably still have been tearing my hair out in frustration with the hot box without your help.

Lastly, I would like to thank my family and friends for moral and not so moral support; you all know who you are…

Trondheim, February 2015

Steinar

SUMMARY

Windows are a key component in the building envelope. They are often, thought of as energy drains and something associated with excessive energy demands in a building. However, in order to assess the energy performance of a window, several factors must be addressed. The most important issues to consider are energy losses due to heat transmission through windows, energy gains from solar radiation as well as transmitted visible light and the influence on artificial lighting demands. Factors like thermal and visual comfort in buildings are additional factors that need to be assessed and addressed.

Existing work that has been carried out within this field of topic lacks in addressing two major factors that are important in the context of this thesis:

- Buildings situated in cold climates.
- Buildings with highly insulated envelopes.

Thus, the need for further research with these aspects in mind emerges and performance assessments of the glazed elements by themselves as well as in combination with shading systems have been carried out. Focus has been on both the thermal and optical performance of systems, and systems performance assessments for whole buildings.

The objective of this thesis has been to investigate the performance of windows and various window solutions in the context of low- or zero-energy buildings situated in a cold climate. Both state-of-the-art solutions as well as more theoretical studies of what today's and tomorrow's windows can look like are studied. Experimental research has been used in combination with numerical simulations to assess and characterize the performance of windows and solar shading devices. The component-level performance characteristics have been used as input to the analysis on the whole building scale for selected case studies. Likewise, the case study results have been used as a baseline for design criteria for components.

One of the aims for the future is to develop solutions for the transparent components of the building to take advantage of highly insulating multi-pane glazing, thus minimizing heat losses. At the same time, the potential energy and lighting gains from solar radiation should be harvested and utilized for heating and lighting.

The case studies showed that the thermal properties of the glazing units play a vital role when trying to reduce energy demands in office buildings. Based on this, a choice was made to investigate the possibilities of improving the thermal transmittance values for glazing units. A review of currently available technologies providing low thermal transmittance values was also carried out.

One of the main results from the simulation work is that cooling demands are becoming a dominating factor in office buildings with well-insulated envelopes, even in what is commonly considered to be a heating-dominated cold climate like Oslo in Norway. Hence, it is important that the design of the window and glazed façades used in such buildings takes into account not only thermal properties, but also optical properties

related to solar insolation. Low window U-values combined with an SHGC close to 0.4 were found to be the optimum for the sample office building situated in a cold (Oslo) climate. This ensures an optimal balance where as much as possible of the useful solar gains are harvested while, at the same time, the solar gains that lead to cooling demands are kept at a minimum. These findings support the need for a more holistic assessment of both thermal and optical properties of windows. However, the Norwegian building regulations only focus on the thermal transmittance of windows and not the solar gains and visible transmittance in an explicit way. Future regulations should be clearer in addressing these aspects when both thermal and visual conditions are considered.

The debate related to the introduction of the passive house concept in Norway has been coloured by a certain disregard for windows. It has been a common perception that window areas should be minimized in order to reduce the energy demand of passive houses. However, modern windows can perform well in low- or zero-energy buildings. Windows with 4-pane IGUs will be equal to or even better than highly insulated opaque walls (i.e. equal to passive house standard insulation level) with respect to the total heating and cooling demands in the sample office building. This shows that it could be possible to move away from passive houses with small window areas by using state-of-the-art windows, thus expanding the flexibility in the architecture, design and layout of future low- or zero-energy buildings.

The choice of shading control strategy can have significant impacts on the energy demand of offices. Depending on strategy, the energy demand can either increase or decrease compared to an unshaded office cubicle. The potential for reduction of energy demands was found to be as large as 9 % if the right shading strategy is chosen. Furthermore, it was found that the improper use of shading systems will lead to an increase in the total energy demand. This increase in energy demand can be as high as 10 %. Hence, it can be concluded that the wrong use of shading systems will lead to an increase in the total energy demand. This is caused by the fact that the wrong shading strategy will block more of the beneficial solar gains than the unwanted solar gains leading to cooling demands. In addition, glare problems must be addressed and reduced to an acceptable level.

Thus, it becomes obvious that modern buildings and the demands of its users make shading devices necessary in order to maintain visual and thermal comfort and also to reduce cooling demands during certain periods of the year. The introduction of controllable solar shading systems is therefore vital to reducing the energy demands; however, such shading devices should not be used without careful planning.

Improving the energy performance of windows should not be seen as an exercise in adding more and more layers to the insulated glazing units (IGUs), even though a building's total energy demand reductions can be as high as 20 % if double-pane glazings are replaced with four-pane glazing units. Likewise, if a triple-pane unit is interchanged with a four-pane glazing unit, total energy demand reduction was found to be as high as 7 %.

A major argument against multi-pane IGUs (with four or more layers) is that the weight will increase and make transport, handling and mounting of windows impractical or impossible in addition to extra loads on the load-bearing structure of the frame and surrounding structure. Also, visible solar transmittance will be reduced and the inhabitants' visual perception of the IGUs will likely be impaired. It was found that the only practical way of reducing the thermal transmittance of IGUs without adding additional glazing layers is to reduce gas thermal conductivity. This could be achieved by reducing the gas pressure in the cavities and thus moving towards vacuum glazing. Another alternative to improve thermal properties is by adding glass layers while at the same time trying to keep the weight of the units low. Using thinner glass layers is a possible solution to this. However, for the layers to be effective, it is vital that the beneficial surface properties from the traditionally low-emissivity coated glass panes are kept. This leads to challenges for extremely thin glass layers, with thicknesses as low as 0.1 mm.

As a supplement to the theoretical studies which were performed, measurements were carried out for two selected technologies.

The possibilities of using in-between pane shading devices to reduce the thermal transmittance of the glazing units when deploying the shading slats were investigated. The effects of operating the shading devices with various slat angles and blind positions were studied. A reduction of U-values when deploying the shading devices were found to be in the magnitude of 1 to 3 %, making it marginal from a global perspective. Taking into account the thermal bridging effects formed by the shading devices themselves, there are even fewer benefits to this system if the aim is to reduce the thermal transmittance value of the windows. Any beneficial effects expected to be achieved by using integrated venetian blinds as an additional layer in the IGU were found to be counteracted by the thermal bridging of the shading hardware. Hence, shading devices with properties like the ones measured (with aluminium slats) should not be considered as an effective system for reducing the U-values of windows. However, several actions could be taken to improve the efficiency of the shading devices.

As a second system with a novel glazing system incorporating phase change materials were also studied. For this kind of product, one is moving away from the traditional notion of windows, as the product is no longer transparent and only a translucent appearance is maintained, but it nonetheless shows some interesting properties which should be taken into account. The utilization of thermal inertia in direct coupling with incident solar radiation is a relatively new concept, but the aim is still to reduce energy demands in the buildings in which it is installed. Another strategy for reduction of energy demands and improvement of comfort in buildings is through the use of thermal mass. A study was carried out where the thermal mass is coupled with a transparent façade element. The element encompasses a layer of phase change material together with a solar shading device in a four-layer glazing unit. The results showed that the latent heat storage capacity of the PCM layer was utilized during a climatic load similar to that of a Norwegian summer day. Beyond this, further studies need to be carried out in order to understand and describe the entire effects of such a system. However, these studies have given results that indicate that the methods used for characterization of the transparent façade element are relevant and that the results form a good base for further studies of such technologies.

This work has shown that transparent facades in future low-energy, nearly-zero or zero-energy office buildings can have good energy performance provided they are well planned with respect to glazing technology, constructions and materials and solar shading solutions.

Contents

1 INTRODUCTION

1.1 Background

Energy demand in the building stock in Norway represents about 40 % of overall energy consumption [1]. Based on the fact that such a substantial part of the final energy consumption is related to the building sector, it is obvious that one should seek to minimize the energy demand associated with the Norwegian building stock. This view is shared by The World Commission on Environment and Development. In their publication from 1987 [2], they write the following (p. 199):

> *"Buildings offer enormous scope for energy savings and perhaps the most widely understood ways of increasing energy efficiency are in the home and workplace."*

Furthermore, a report published by McKinsey [3] concludes that refurbishment and improvement of the energy performance of buildings is one of the most cost-efficient ways of reducing global CO_2 emissions.

The building sector is commonly accepted to have enormous energy savings potential [2]. Furthermore, in the recommendations given by the International Energy Agency, the primary action for lowering energy use in the construction sector should be to reduce the need for energy, as shown in the so-called "Kyoto pyramid" [4]. Already at this point, one can clearly see the need for research and development in the energy performance of the building envelope (the exterior parts of the building).

A substantial part of the energy use and climate-gas emissions in the construction sector is directly related to the construction, operation and decommissioning of the actual buildings [5]. New building regulations and legislation constantly tighten the demands for energy use for building operations [6].

Even moving towards passive house-level envelopes [7], zero-energy buildings or zero-emission buildings as defined by the Research Centre on Zero Emission Buildings (ZEB Centre) [5, 8, 9] where the carbon footprints of the buildings have been reduced vastly, the performance of the transparent parts of the envelope is vital in order to ensure a low energy demand and a desirable indoor environment [10, 11].

Previous studies have explored and confirmed that the energy performance of buildings is highly dependent on the design, functionality and area of the transparent façades in office buildings [12-14].

Based on the recommendations given in IEA ECBCS Annex 44 and the "Kyoto Pyramid" [4], combined with the fact that windows contribute to a substantial part of heat losses, one should further investigate the possibilities of reducing heat loss and improving the performance related to all glazed and translucent parts of the façades.

Focusing solely on heat loss through the glazed parts of the envelope, Grynning [15] found that heat loss related to windows contributes over 40 % of the total heat loss through the building envelope for a typical Norwegian office building constructed according to Norwegian building regulations [16]. This makes it highly relevant to explore potential technologies and systems that could be used for improving performance and reduction of heat loss.

The glazed areas can make a positive contribution to the energy balance of the buildings by letting solar energy in and reducing heating demand at certain times of the year. However, the use of glazed parts and components in a façade can also give rise to a cooling demand in the buildings.

When optimizing the glazed area, complex interactions must be taken into account. As Ochoa et al. [17] point out, a set of clearly defined evaluation criteria must be set prior to any energy and/or daylight optimization tasks. Their study looks at the optimization of window size in a sample office cubicle, and the authors propose using glare and illuminance uniformity as criteria for visual comfort, whereas total energy consumption and illuminance should be considered when meeting legal requirements, for example. Furthermore, a clear set of assessment criteria for the solution space should be defined prior to any assessments.

Improved energy efficiency of buildings is vital in reaching the goal of reduced global CO_2 emissions. Building regulations are being tightened and insulation levels in the building envelope are steadily increasing. As insulation levels increase, the traditional view that Norway has a primarily heating-dominated climate is not necessarily the case anymore. Lower transmission heat losses combined with internal gains create a more cooling-dominated situation in Norwegian buildings. This is especially the case for offices because internal gains are still high, due primarily to computers and user density.

Transparent parts are vital elements in the building façade as they provide the visual link between the exterior and interior environment of the building as well as providing daylight. A general *a priori* attitude among building practitioners is that large windows will lead to high cooling demands during the warm period of the year and large heating demands during the heating-dominated period of the year. However, not many scientifically sound studies which discuss the whole situation have been found in the literature.

Windows in building envelopes

Windows are a key component in the building envelope. They are often, as discussed in the previous section, thought of as energy drains in a building. However, in order to assess the energy performance of a window, several factors must be addressed. The most important issues to consider are energy losses due to heat transmission through windows, energy gains from solar radiation as well as transmitted visible light and the influence this has on artificial lighting demands. Factors like thermal and visual comfort in buildings are additional factors that need to be assessed and addressed.

It is a general understanding that heat loss through the transparent components of the building envelope constitutes a large part of the total heat loss of a building. There is, however, more to the situation. When considering the thermal performance of the transparent areas, one should also include the beneficial effects of incident solar radiation and the impact on heating and cooling demands as well as artificial lighting. In spite of this, as an example, the Norwegian building code only sets requirements for the U-value of glazed parts of the building envelope, and specifies in general terms daylight comfort demands and that actions should be taken to avoid local cooling.

One of the aims for the future should be to develop solutions for the transparent components of the building to take advantage of highly insulating multi-pane glazing, thus minimizing heat losses. At the same time, the potential energy and lighting gains from solar radiation should be harvested and utilized for heating and lighting.

2 LITERATURE REVIEW

2.1 Windows and glazed façades in office buildings

2.1.1 Energy performance

Windows are key elements in buildings with an explicit goal of reducing energy demands both during operation and for material use. Previous studies show that a large part of the net energy demands of an office building is related to window heat loss and cooling demands induced by solar irradiance [11, 15, 18].

Investigations into the energy performance of windows have been performed in several studies. Residential buildings are the dominant type of building to have been studied. However, a clear distinction between residential and other buildings should be made. Residential buildings differ from commercial buildings in several aspects. Here, two are mentioned. Firstly, residential buildings have lower internal gains. Secondly, in general, no cooling equipment will be installed in residential buildings. For office buildings, it is crucial to investigate how the window design and its properties affect the combined cooling and heating demand as well as challenges related to daylight and the distribution of daylight [12]. This makes the performance related to internal gains, geometry and any other elements in the energy balance of the building more complicated. The energy balance and energy performance, as such, of windows is a complex interaction of heat flows and solar radiation. Hence, it is crucial to have holistic assessments where all of this is accounted for.

As found by previous authors, substantial energy savings potentials are present as a function of building envelope optimization. If one looks at the savings related to the transparent parts (e.g. windows) of the envelope, Winther [11] found that the total energy demand for heating, ventilation and cooling (HVAC) and lighting of an office building in a Danish climate varied between 96 kWh/m² and 73 kWh/m² depending on combinations of the thermal and optical properties of the glazed parts of the building. The lowest energy demand was found for a case with a lowest possible U-value, combined with a low solar heat gain coefficient and automatic lighting controls. No shading devices were included in this part of Winther's study.

In a study investigating façade design principles in nearly zero-energy buildings, Thalfeldt et al. [18] found that for an office building situated in the Danish climate with conventional windows (e.g. with 2- and 3-pane glazing units), heating demands dominated the energy balance of the building. However, when improving the thermal properties of the window and reducing U-values to 0.2–0.3 W/m²K (e.g. windows with five- or four-pane glazing units), heat losses became negligible as the thermal insulation level was similar to that of the opaque parts of the envelope. The four and five-pane glazing units studied, had solar heat gain coefficients 0.36 and 0.24 respectively. The optimal window to wall ratios (WWR) found, were as follows:

- South-facing, 5 panes, WWR = 60 % without shading.
- East-facing, 5 panes, WWR = 60 % with external shading.
- West-facing, 5 panes, WWR = 60 % with external shading.

- North-facing, 5 panes, WWR = 60 % with external shading.

These results indicate that the primary design optimization of the transparent façades in cold climates should be to improve the window thermal performance. It also highlights that shading becomes less important (from an energy demand point of view) as the insulating levels of the windows are improved.

Dubois [19] carried out a study that investigated energy use for heating and cooling of an office room equipped with different solar-protective glazings. The room's orientation, the glazing-to-wall area ratio (GWAR) and the climate were alternately varied and the impact of these parameters on annual energy use, peak demand and indoor temperature were studied. The thermal transmittance (U-value) of the opaque walls surrounding the glazing units were adjusted so that the average U-value of the entire façade was kept constant at 0.99 W/(m²K). The author found that for south- and north-facing façades with 30 % GWAR, glazings with high solar transmittance (SHGC > 0.6) yielded lower annual energy use than average transmittance glazings (SHGC between 0.4 and 0.6). This is because cooling demands were offset by large reductions in heating demands. On east- and west-facing façades, however, average transmittance glazings (0.4 < SHGC < 0.6) performed better than glazings with high transmittance values. Furthermore, it was found that south- and north-facing façades had lower annual energy demands with a larger solar aperture than east- and west-facing façades, indicating that larger glazing areas or a higher shading coefficient should be selected on south- and north-facing façades. The study does not include daylight utilization and the effect on artificial lighting demands. Nor does it include aspects related to thermal and visual comfort in the studied office cell.

Poirazis and Poirazis et al. [12, 20] have done energy simulations for an extensive amount of different glazing and solar shading solutions for an office building in Sweden. The results presented indicate that there is indeed an energy savings potential affiliated with the use of shading systems. The effect of the solar shading on the thermal performance depends on the glazing system area and U-value. If the U-value decreases, the effect of the solar shading system will also decrease. Future buildings must, however, make use of windows with lower U-values than the ones used in the calculations performed by Poirazis [20] and Poirazis et al. [12].

In a study presenting design guidelines for office buildings [21], a parametric study of key envelope parameters of an office building situated in Uccle, Belgium was carried out. The authors conclude that the following actions should be taken when optimizing the design of the office building: insulate the building and have good airtightness, limit and control internal gains, carefully choose window size and orientation, ensure there is adequate ventilation, and address thermal inertia. In particular, they write about the window optimization challenges (p. 490-491): "*Since simulations showed the great influence of the internal gains on the cooling loads and since a mean to reduce those is the use of daylighting, it would be judicious to increase glazed surfaces, but that must be done with some care and the choice of the glazing must be quite considered*". This underlines the above-mentioned complexity of window optimization in office buildings. However, the building studied is relatively poorly insulated, with 7 – 10 cm insulation thicknesses in the opaque parts of the envelope, compared to Norwegian standards which typically need 20-40 cm insulation in order to reach building regulations [16] or passive house levels [7].

2.1.2 Daylight performance and artificial lighting

For an office building situated in Tallinn, Boyano et al. [22] found energy savings potentials of 20 % when installing artificial lighting controls based on available solar lighting levels. Likewise, an energy demand reduction of 10 % was found when improving windows from 2- to 3-pane glazings, with U-values of 3.6 W/m²K and 1.8 W/m²K for 2- and 3-pane glazings respectively. However, this study was carried out for windows with rather poor properties compared to the modern windows used in Norwegian office buildings. The resulting effects on energy demands as a function of further improvement possibilities for the glazed façades should be explored.

In a similar study [23], it was found that proper utilization of daylight could reduce the need for artificial light by 50 to 80 %, and that the total primary energy demand of the office could be reduced by approximately 40 %. Similarly, energy savings potentials of 40 to 55 % were found by Bülow-Hübe [13] if well-designed daylight dimming systems were used. These studies underline the importance of keeping track of the visual properties of the windows alongside the thermal parameters and performance. However, the buildings studied are relatively poorly insulated with high U-values. Thus, it does not give a representative picture of a building constructed with a well-insulated envelope (e.g. passive house levels). The window properties are also somewhat outdated with higher U-values and lower corresponding solar heat gain coefficients (SHGCs) than what is achievable and more common with today's state-of-the-art windows.

2.1.3 Rating methods

Several simplified methods for assessing the performance of windows in a simpler way have been proposed with the aim of classifying window performance on a more general level.

A Swiss study [24] suggests a simplified model where the characterizing the quality of a glazing unit is based on the ratio between total solar energy transmittance and thermal transmittance (g/U). The ratio between interior-exterior temperature difference and solar irradiance ($\Delta\theta/I$) are used for characterization of the severity of the climate. The method is based on monthly mean values of interior-exterior temperature difference and solar irradiance.

Spanish researchers [25] have presented a window energy rating system where they studied the useful energy for heating of the building as a function of the climate and building type. An annual useful solar heat gains factor is used as the base for the window energy rating. The authors [26] define a characteristic parameter, the balance temperature, T_b, which is a function of solar radiation levels, internal gains, total heat losses and the time interval considered.

An Italian study presents three separate building cases in five different Italian climates in order to introduce a rating scheme [27]. The ratings proposed are functions of window properties, climate conditions and the architectural characteristics of the residential building. Both cooling and heating loads were considered with the use of detailed whole building energy demand simulations. The simulation results were used to define a simplified algorithm using different regression approaches which can be used to rate the window heating- and cooling-load reduction potentials. The analysis has been performed on windows with U-values of 2.6 W/(m²K) and higher and it does not discuss how other building types and/or climate conditions would influence the rating factors found in the regression analysis. The authors point out that further investigation into the energy rating schemes is required.

A net energy gain value for residential buildings, has been proposed in Denmark [28]. Here, they present a method to account for both heat losses and heat gains through a window based on the U-value and the g-value (the same as the SHGC).The method proposed by the authors [28] is a simplified model, which is valid for the heating season only. Thus making it less suitable for buildings where a cooling demand is prominent during warmer periods of the year. In these periods solar gains might give a negative contribution to the energy balance of the building by increasing cooling demands.

Through the IEA-SHC Task 27, a Canadian workgroup proposed a simplified energy rating model for windows [29]. Here, they also present an overview of which parameters must have a clear and specific measure in order to be able to characterize an energy efficiency level. The parameters are U-value, SHGC, visible transmittance (T_{vis}) and condensation resistance. Based on these parameters, a simplified equation is proposed which is used to calculate the energy rating (ER) of the windows. However, the rating method is valid only for the heating season, and the multiplication factors to account for average solar radiation and temperature difference are calculated for Canadian climates only.

Aside from the Italian method, all the simplified methods only consider the energy balance during the heating season of the year. This might be adequate for residential buildings, but not for buildings with cooling loads. Good performance during a period with a negligible cooling demand might not necessarily indicate a good performance during the cooling-dominated period of the year. It is a fact that office buildings with a large amount of transparent surfaces facing south will have a cooling demand during extensive periods of the year, even in a cold climate like Norway [30]. Furthermore, one can see a clear similarity between the Danish and the Canadian method. The energy rating for both methods revolves around accounting for solar gains as a positive contribution and heat losses as a negative factor. The main difference is that the Canadian method accounts for air leakages related to the windows as a separate term.

The Danish, Spanish and Canadian methods all describe simplified models with a somewhat generic usefulness, but they all have limitations in that they are applicable only to residential buildings where cooling loads are minor. The Italian method describes the procedure for rating both the cooling and heating performance, but it is limited in that it is based on regression analyses for only a limited number of climate conditions and windows with a high U-value of 2.6 W/(m²K).

2.1.4 Window component performance

One major disadvantage of highly insulated glazing units (IGUs) is the steadily increasing weight of the IGU. Adding more layers increases the weight, creates difficulties with transport and mounting, and operating the windows once in place may become impractical and cumbersome. In order to maintain the favourable thermal and optical properties while keeping the weight of the IGUs at an acceptable low level, a solution would be to use non-structural intermediate layers in the IGU. The outer panes can be kept as thick as needed for maintaining the function of structural integrity, safety, soundproofing, fire resistance, etc., while the thickness of the intermediate layers can be reduced because they do not need to have any structural integrity other than being self-supportive. Applications using polymer-based foils and thin glass layers have been found in the literature. Practical examples of such glazing units will be further discussed within this study. An alternative to the thin film or thin glass technologies is the application of lightweight glass materials. Although interesting, the development of such new glass materials is novel and in its infant stage. Tao et al. [31, 32] has explored the possibility of incorporating aerogel granules in float glass in order to reduce the weight of glass panes. The authors found that the weight of a glass pane could be reduced by almost 30 % compared to normal float glass while at the same time maintaining a high visible transmittance of approximately 95 % at 500 nm.

Using suspended foil is a promising window technology that is starting to permeate the market. Here, intermittent glazing layers in an IGU are replaced with several thin, polymer films. This contributes to a substantial weight reduction of the glazing units compared to their all-glazed counterparts, hence leading to the possibility of producing reasonably lightweight, highly insulating units. The suspended foil technology is not very common among the normal insulated glazing units but their very good thermal insulating properties could make them especially suitable for cold climates.

Window glazing and the various related aspects are addressed in several studies. In two recent review articles of fenestration products, Jelle et al. [33] and Cuce and Riffat [34] present, among other topics, current and future glazing technologies. Multilayer glazing units using conventional float glass, suspended film technologies and ultra-thin glass technologies for future applications in glazing units are also discussed, for example fenestration technologies of both today and tomorrow [33]. Cuce and Riffat's [34] main finding regarding this topic is that the solar transmittance in multilayer glazing units is largely governed by the surface properties of the glass panes and that the effect of the glass thickness is negligible. Solar radiation glazing factors including electrochromic windows are studied in [35], miscellaneous energy aspects of windows and window frames in[36, 37], and a state-of-the-art review and future perspectives on window spacers and edge seals in insulating glass units in [38].

Work carried out at Lawrence Berkeley National Laboratories (LBNL) [39] includes studies of window prototypes utilizing a suspended foil in-between structural glass layers. Arasteh et al. [39] report that a three-pane glazing unit using non-structural suspended layers in-between the outer glass panes yields glazing units with the same thermal performance as traditional three-pane IGUs but with a substantial weight reduction.

The focus of the optimization study carried out in this work [39] is that of improving the thermal and optical properties of the windows in order to reduce the energy demand for buildings. Furthermore, it is obvious that reducing the amount of glass in the windows by reducing glazing layer thicknesses will reduce the need for raw materials and thus improve the carbon footprint of the window. Further elaboration of this is, however, not within the scope of this work.

The scope of this study relates to glass technologies and performance. The total performance of a window is made up of three main components: the glazing unit, the frame and the spacer. With respect to frame and spacer technologies, suggested reading can be found in various studies in the literature [37, 38, 40].

2.2 Shading systems in office buildings

Modern office buildings often have large glazed areas towards the exterior where the glazed parts of the envelope can constitute a substantial part of the total envelope area. This makes them especially exposed to and dependent on solar radiation, which can lead to large cooling demands during hot, cooling-dominated periods. On the other hand, the solar radiation can help reduce heating demands during heating-dominated periods.

Previous studies also show that large parts of the net energy demand of an office building are related to window heat loss [15] and cooling demands induced by solar irradiance [12, 20]. The authors found that, even in what traditionally has been considered to be a heating-dominated climate, cooling demands dominate the net energy demand of an office building. Solar shading measures are vital to reduce the cooling demand of an office building.

2.2.1 Shading system – main categories

Internal shading systems

Internal solar shading systems have in general been assumed to have a limited influence on the thermal transmittance through glazed façades with low U-values, i.e. the U-value is not significantly influenced [41]. However, measurements using a hot box indicated that by mounting blinds to the window, the effective U-value of a double-pane glazing system was reduced by approximately 5 % compared to the unshaded window [42]. Measurements done by Fang [43] confirm that an increase in the reflectivity of the (venetian) blinds will reduce the effective U-value of the glazing system further. The effect will nevertheless be smaller than for an external shading system [41].

The main reason for using internal solar shading should therefore be to control glare and to some extent the visible light transmission through the glazed area (as the solar gains through the windows do not change with internal shading systems). If the aim is to reduce U-values and heat loss, other positions should be considered.

In-between pane shading systems

One of the benefits of in-between pane shading systems is the potential effect on the U-value of the glazing system. If the system is constructed in an optimal way, the shading screen may act as an additional layer of the glazing system, e.g. two-pane glazing will, in some limited manner, act as three-layer glazing. Rosenfeld et al. [44] present results from both calculations and measurements that show a potential for reducing the total solar energy transmission by approximately 30 % for a double-layer glazing system, depending on the angle of the lamellae in the blind and the angle of incident solar radiation. However, Laouadi [41] concludes that slat-type shading made of metal might introduce substantial thermal bridges, thus increasing the U-value. Furthermore, Laouadi concludes that the use of plastic as the slat material may reduce the U-value of two- and three-pane glazings by as much as 20 %. Measurements performed by a commercial producer of shading systems on a two-pane glazing system indicate that the U-value could be reduced from 1.2 W/m^2K to 0.8 $W/(m^2K)$ by mounting an airtight solar shading screen inside the gas-filled cavity, acting as a third pane of glass in the closed position [45].

External shading systems

Detailed calculations for solar transmittance through exterior slat-type blinds are complex, as is the case for interior-placed slat-type blinds. Several studies have been performed where factors like slat geometry, angle and emissivity of surfaces have been implemented in the calculation methods. The effect the albedo of the surrounding surfaces has on the transmitted energy (g-value) has also been discussed in some studies [46]. As for the internal shadings, screen shadings and roller blinds might also be applicable for an external shading system.

Shading systems summary

In general, external shading devices perform better than internal shading devices in terms of reducing and controlling solar gains [47]. To function properly, the internal shading needs to be highly reflective in order to reflect the heat effectively back out through the window/glazing area. However, the rather small relative effect of internal shading will decrease even more as the insulating performance of the glazing increases. In conclusion, this means that externally placed shading systems might be even more interesting in low- or zero-energy buildings of the future, where the U-value of the windows is low.

2.2.2 Control strategies of shading devices

As found in several earlier studies, automatic control of shading is a key to realize the energy savings potential and daylight benefits of the shading systems and that the control methods must include both lighting and cooling energy simultaneously [48]. This should ideally be extended to also include heating energy. Manual control should be avoided from an energy saving point of view, as users of the buildings tend to leave the blinds in either open or closed positions regardless of what is optimal with respect to cooling/heating need and or daylight levels [49, 50].

Furthermore, the choice of strategy is important in order to optimize utilization of solar gains. Several studies have been performed where control strategies and patterns of various shading systems have been studied [51-54]. In [55], it was found that in order to reduce heating demands during winter, a combination of solar irradiance levels and internal temperature set points should be used. This will ensure better utilization of solar gains for heating during wintertime.

Existing studies [14, 56] found that control strategies are not without flaws, making for higher real energy consumption than predicted from simulations. The sensitivity analysis performed in this work [56] sheds light on how to better accommodate user behaviour in the design of shading control strategies and how to make the control strategies more robust, focusing on a cold climate.

2.2.3 Novel shading systems – phase change materials

In recent years there has been an increasing interest in and amount of research carried out regarding fairly new technologies like phase change materials (PCMs). A PCM in a building context is usually a material that has a melting point in the region close to the comfort or operational temperature in the building where it is adopted. The latent heat storage potential in the phase transition between liquid and solid state can thus be utilized as heat storage and shows favourable behaviour in terms of increasing the thermal inertia of the system. The raw materials used to produce PCMs can be divided into three main groups: eutectic, organic and in-organic materials [57]. For the use of PCMs in windows, paraffin-based organic materials are the most interesting, since they are transparent in the liquid state and translucent in the solid state.

Some studies concerning PCMs in combination with glazing have previously been performed. These range back to 1997, with a study of a PCM layer coupled with a transparent insulated material [58]. The aim of including a PCM layer in a transparent system is to collect (a large part of) the near infrared (NIR) solar radiation (that does not contribute to daylight) within the PCM layer itself and let (the largest part of) the visible solar radiation enter the indoor environment, thus still allowing natural light exploitation for daylighting purposes. This behaviour is achieved thanks to the highly selective optical properties of some PCMs, e.g. paraffin wax. An investigation of the optical properties of PCM layers in combination with glazed layers was carried out, by means of a large integrating sphere facility, by Goia et al. [59], who characterized different thicknesses of the PCM and the angular-dependence of the coefficients.

The use of PCMs as moveable shutters was studied by Ismail and Henriquez [60]. Here, PCMs are pumped to and from a storage tank underneath the window. The authors conclude that a PCM-filled window is thermally more effective than an air-filled window as it filters out thermal radiation which in turn reduces heat gains or losses. Weinläder et al. [26] performed measurements on double glazing with a PCM acting as a third (internal) layer to the glazing unit. The authors found that a reduced heat loss compared to the double-glazing unit is mainly due to the additional cavity behind the PCM. They also found a slight shift in peak energy flows when using the PCM, but the authors concluded that if the heat gains of double glazing (higher at mid-day) can be stored, it might overcompensate for the high heat losses in this system. However, the addition of a PCM has a positive effect on thermal comfort by dampening the extreme temperatures during mid-day and night.

A study where a PCM was used for latent heat storage in an internal slat-blind shading device [61] concluded that there is substantial cooling potential during the summer and also some benefits during the wintertime, compared to a conventional material blind. The PCM used here is not transparent; rather, it is used in combination with a window, thus making it part of a transparent component. Likewise, a numerical simulation study for externally placed shutters with PCMs [62] concludes that the heat gain through the window can be significantly reduced when mounting shutters with PCMs compared to an unshaded window.

A comparison of two-pane windows with a gas-filled cavity and a PCM-filled cavity was performed by Ismail et al. [63]. They found that double pane windows could reach lower U-values than similar PCM filled windows. SHGC-values were, however, found to be in the same magnitude for windows with and without PCM. Goia et al. performed an experimental analysis on a double-glazing system with paraffin wax by means of an outdoor test cell facility located in a temperate sub-continental climate [64]. Implications of this system on thermal comfort conditions were also investigated starting from experimental data [65], and a physical-mathematical model [66] for simulating PCM glazing systems was developed too. Recently, Gowreesunker et al. [67] analysed the optical and thermal properties of a small-scale PCM-glazed unit, assessing its performance using combined experimental-numerical analysis. The investigation focused on the relationships that describe the extinction, scattering and absorption coefficients within the phase change region, validated in a numerical CFD model.

2.3 Literature review – summary

If one summarizes the literature presented in this review, it is clear that the need for further research is present. The previous work that has been carried out largely fails to address two major factors that are important in the context of this thesis:

- Buildings situated in cold climates
- Buildings with highly insulated envelopes

Thus, the need for further research with these aspects in mind emerges and performance assessments of the glazed elements by themselves as well as in combination with shading systems should be carried out. Focus should be put on both the thermal and optical performance of systems and systems performance assessments for whole buildings.

3 THESIS OUTLINE

3.1 Research objective

The objective of this thesis has been to investigate the performance of windows and various window solutions in the context of low- or zero-energy buildings situated in a cold climate. Both state-of-the-art solutions as well as more theoretical studies of what today's and tomorrow's windows can look like are studied. Experimental research has been used in combination with numerical simulations to assess and characterize the performance of windows and solar shading devices. The component-level performance characteristics have been used as input to the analysis on the whole building scale for selected case studies and likewise, the case study results have been used as a baseline for design criteria for components.

3.2 Research questions

The key research topics were defined and formulated based on a thorough literature review.

1. To what extent is it possible to reduce the energy demand of low-energy, nearly-zero or zero-energy office buildings of the future through the design of the transparent parts of the building envelope?
2. Will energy demand reduction measures influence the perceived comfort in the buildings?
3. Is it possible to establish and specify optimal combinations of solar and thermal performance characteristics of windows in low-energy, nearly-zero or zero-energy office buildings in a Nordic climate and will the characteristics of the baseline change if dynamic systems are introduced?
4. What are the enabling technologies for reaching these targets?

3.3 Scientific papers

The main research of the thesis is structured around the work published in six scientific papers. One paper was presented at a peer-reviewed scientific conference, whereas the remaining five have been published, accepted by or submitted to peer-reviewed scientific journals.

1. S. Grynning, A. Gustavsen, and B. Time, "Solar Shading Systems and Thermal Performance of Windows in Nordic Climates", *9th Nordic Symposium on Building Physics*, Tampere, Finland, 29 May–2 June 2011.

2. S. Grynning, A. Gustavsen, B. Time, and B.P. Jelle, "Windows in the buildings of tomorrow; Energy losers or energy gainers?", *Energy and Buildings*, 61, 185–192, June 2013.

3. S. Grynning, B. Time, and B. Matusiak, "Solar shading control strategies in cold climates – Heating, cooling demand and daylight availability in office spaces", *Solar Energy*, 107, 182–194, 2014.

4. S. Grynning, F. Goia, E. Rognvik, and B. Time, “Possibilities for characterization of a PCM window system using large scale measurements”, *International Journal of Sustainable Built Environment*, 2, 56–64, 2013.

5. S. Grynning, C. Misiopecki, S. Uvsløkk, B. Time, and A. Gustavsen, “Thermal performance of in-between shading systems in multilayer glazing units – Hot-box measurements and numerical simulations”, accepted for publication in *Journal of Building Physics*, 10.10.2014.

6. S. Grynning, B.P. Jelle, A. Gustavsen, T. Gao, and B. Time, “Multilayer Glazing Technologies: Key Performance Parameters and Future Perspectives”, submitted for publication.

3.4 Thesis work structure

The working progress of this thesis is divided into two main parts as shown in Figure 1.

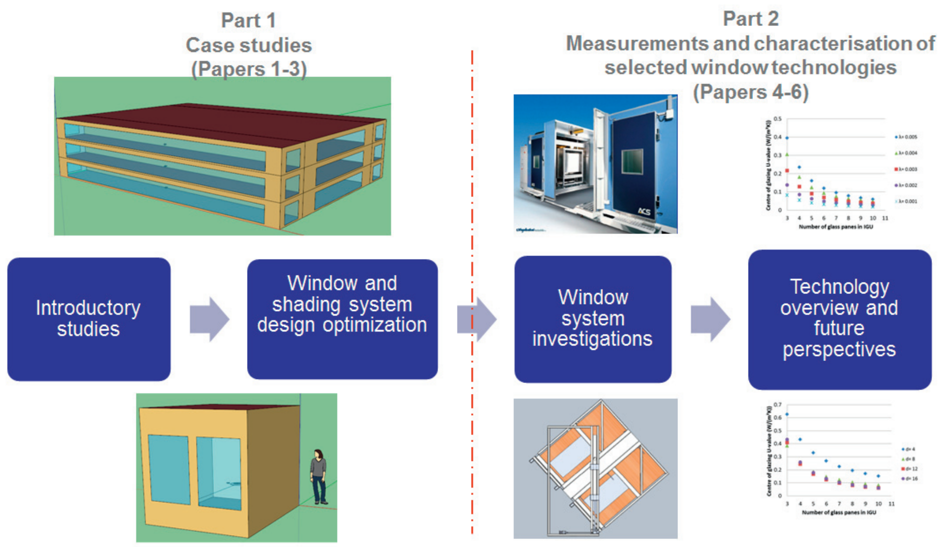


Figure 1. Research structure illustration.

The parts should not be considered as a chronological list of the working process, but more as a schematic way of structuring and presenting the results obtained throughout the entire working period. The work has, in reality, been an iterative process where ideas and results have been exchanged back and forth between the structural phases.

3.4.1 Part 1 – Case studies

In this part of the thesis work, the whole building and component-level performance were studied using whole building energy simulation tools. Energy performance and comfort for a sample office building and two selected office cubicles were investigated. Performance studies were based on parametric studies for window and shading systems and methodologies were developed and assessed. The results were published in papers 1–3.

In paper 1, a preliminary study was carried out with the aim to study energy demands as a function of different shading strategies using a simplified simulation tool. The simulation tool SIMIEN [68] is based on the dynamic calculation method described in the Norwegian standard NS 3031 *Calculation of energy performance of buildings – Method and data* [69] and validated according to NS-EN 15265 *Energy performance of buildings – Calculation of energy needs for space heating and cooling using dynamic methods – General criteria and validation procedure*s [70]. It is, however, a simplified tool where the actual geometry of the buildings is not accounted for. One of the main conclusions was that a more advanced tool was needed in order to properly assess the large number of questions that arose, which led to the work carried out in paper 2.

Paper 2 presents the energy demands of an office building as a function of the thermal and optical properties of windows. As a first level of complexity, windows without shading devices were studied. The simulations were carried out using the simulation tool Energy Plus [71]. Results showed that windows can perform well in terms of energy demand in the sample office building.

The results from paper 2 led to the work carried out in paper 3. Here, the complexity of the transparent façades were increased and an integral study of energy demand for heating, cooling and artificial lighting demands for representative office cubicles was carried out. The choice to move away from whole building energy simulations in favour of single room studies was based on the desire to ensure better representation of daylight distributions and thermal comfort assessments. As a result, visual and thermal comfort assessments are presented alongside the energy demand investigations. The choice to study two different geometries of office cubicles was made based on the assumption that two different geometries and user loads would represent a more robust solution space for the assessments. The two cubicles were chosen to represent a typical small, one-person cubicle and a larger two- to multi-person office space.

The results of the studies carried out here form the basic design guidelines which should be aimed for in *real* systems.

3.4.2 Part 2 – Measurements and characterization of selected window technologies

Complementary to the numerical studies carried out in papers 1–3, component-level performance studies for selected and future window technologies have been carried out in papers 4–6. The selection of technologies was made in dialogue with industry partners at the ZEB Centre based on the wish to investigate new and enabling technologies.

Phase change materials (PCMs) are one of several new technologies available for building applications on the market today. They have previously been used commercially to some extent [72-74], but few studies have been carried out where energy savings potential and thermal comfort aspects have been performed. Paper 4 investigated a novel window with integrated solar shading and PCM. This is a complex component, and a suggestion for a characterization procedure using a climate simulator is given alongside benchmarking of the product against an ordinary window.

As a second system, windows with integrated shading devices were studied through experimental work and simulations. Such technologies have been available on the market for several years but there is a scarcity of published work regarding the effect such shading systems can have on the thermal performance of windows. The thermal performance of in-between pane shading devices was assessed in paper 5.

Some key performance criteria for the glazed parts of façades in office buildings were studied in part 1. Based on these criteria, a literature review has been carried out where the aim was to investigate how one can achieve the performance targets found in papers 1–3. This resulted in paper 6, where a study of multi-pane windows was carried out. Promising new technologies were investigated and a parameter study assessing window performance as a function of key physical properties was performed. The paper also looked at future perspectives, optimization work and research possibilities.

3.5 Scope and limitations

The definition and ultimately the performance of low-energy, nearly-zero or zero-energy office buildings are a complex interaction of interdisciplinary topics. It is far beyond the scope of a PhD thesis to investigate and discuss all of these topics. The most obvious argument against such a limitation of scope is that of sub-optimizing. Optimizing, in this case transparent façade and window performance, solely based on the performance of the systems during the operation of the building excludes such factors as embodied energy and the total carbon footprint of such systems over their lifetime. Hence, an optimal solution for a transparent façade based on energy demand during operation might not be the best solution from a total life cycle perspective where embodied energy demands are included as well. In spite of this, a choice has been made to study only the in-operation performance in this thesis. The choice was made based on the fact that the majority of the work carried out is centred on conceptual systems. Thus, it should be considered as the first step in the optimization and design of such systems. In future steps, where practical systems are studied, life cycle analyses of CO_2 emissions should of course be carried out.

The studies in both papers 1 and 2 were carried out for a selected sample office building. The geometry of the building and the envelope levels were chosen based on the wish that the building should represent a typical-sized office that complied with the Norwegian building regulations [16] for the study in paper 1. When the work in paper 2 was carried out, passive house levels in offices had already become more relevant and a separate Norwegian standard for passive house-level office buildings [7] had been implemented. Hence, a choice was made to keep the building geometry from paper 1 but to improve the building envelope and technical systems to comply with this.

4 WINDOW PHYSICS

4.1 Basic heat transfer in windows

The total heat transfer in a glazing unit is the sum of gas convection, conduction and radiation as well as the solid-state conduction in the glass panes. Short-wave radiation (i.e. UV radiation and visible light) is discussed in chapter 4.2. One or more of these heat transfer mechanisms can be reduced in order to improve the thermal performance of the insulated glazing unit (IGU).

Float glass is a relatively good heat conductor, with a typical heat conductivity of $\lambda \approx 1$ W/(mK). Consequently, the bulk of the heat resistance of an IGU is made up of the warm and cold side surface heat transfer resistances (R_{si} and R_{se}), the thermal resistance of the glass panes (R_{gp}) and the thermal resistance of the cavities (R_{cavity}) in the IGU. It is primarily the heat resistance of the cavities that can be increased in order to lower the thermal transmittance (U_{cog} value) of the IGU. The U-value is the inverse value of the total heat resistance of the centre-of-glazing, as shown in Eq. 1 [75].

$$U_{cog} = (R_{cog})^{-1} = \left(\sum_{i=1}^{n} R_{gp} + \sum_{i=1-1}^{n} R_{cavity,i} + R_{si} + R_{se}\right)^{-1} \qquad (1)$$

Where:

U_{cog} = Centre-of-glazing thermal transmittance (W/(m²K))
R_{cog} = Centre-of-glazing thermal resistance (m²K/W)
R_{gp} = Centre-of-glazing thermal resistance of glass panes (m²K/W)
R_{cavity} = Centre-of-glazing thermal resistance of cavity i (m²K/W)
R_{si} = Warm side surface heat transfer resistance (m²K/W)
R_{se} = Cold side surface heat transfer resistance (m²K/W)

The thermal resistance of a single cavity, R_{cavity}, is affected by the sum of the three heat transfer mechanisms: gas conduction, gas convection and radiation.

4.1.1 Gas conduction and convection

Gas conduction is largely governed by the thermal conductivity and thickness of the gas layer in the cavities. The thermal resistance can be improved by increasing the cavity thickness or by reducing the thermal conductivity of the gas filling. Inert gases like argon, krypton and xenon are typical examples of gases with lower conductivity values than air. Argon is the most commonly used gas as both krypton and xenon are rather expensive and not so readily available. Introducing a vacuum in the cavities will more or less cancel gas conduction (as well as convection), but this introduces other challenges, as discussed by Jelle et al. and Manz [33, 76]. The solid-state conduction of the glass panes (in the glazing unit) is governed by the conductivity of the glass or other material used in the panes. The thickness of the glass panes, however, is limited and minor thermal resistance can be contributed to the glass panes compared to the thermal resistance of the cavities.

Convection (internal air flow in the cavity) is caused by the temperature gradient across the cavity. The convection will increase the larger the cavity thickness and temperature gradient and it will be the dominating heat transfer mechanism until a critical cavity thickness is reached. This critical thickness will vary depending on several factors, such as the number of cavities in a glazing unit, the height of the cavity, the temperature gradient across the cavity and the type of gas used in the cavity.

The combined effects of convection and conduction on the heat transfer are characterized by the Nusselt number, the gaseous conductivity and the width of the cavity, as shown in Eq. 2.

$$\Lambda_{gas} = \frac{Nu \cdot \lambda_{gas}}{L} \qquad (2)$$

Where:

Λ_{gas}	= Gas conductive and convective heat transfer	(W/(m²K))
Nu	= Nusselt number	(-)
λ_{gas}	= Thermal conductivity of the gas	(W/(mK))
L	= Cavity width	(m)

The Nusselt number quantifies the convective heat transfer as a function of gas thermal conductivity, cavity dimensions and surface heat transfer coefficients.

4.1.2 Radiation

The radiative heat transfer in a cavity is governed by the surface temperature of the adjacent glass panes and the emissivity of these surfaces. If one assumes surface temperatures typical for building applications and applies the laws of Kirchhoff and Stefan-Boltzmann [77], the resulting radiative heat transfer between two glass panes can be described as shown in Eq. 3.

$$\Lambda_{rad} = 4\sigma T^3 \left(\frac{1}{1/\varepsilon_1 + 1/\varepsilon_2} \right) \qquad (3)$$

Where:

Λ_{rad}	= Radiative heat transfer between two surfaces	(W/(m²K))
σ	= Stefan-Boltzmann constant, given to $6 \cdot 10^{-8}$	(W/(m²K⁴))
T	= Mean surface temperature in cavity	(K)
ε_i	= Emissivity of surface 1 and 2	(-)

Hence, it becomes obvious that the radiation can be reduced by lowering the emissivity of the surfaces, which may be achieved by application of low-emissivity (low-e) coatings. The optical (both visible and non-visible) properties of the IGU will, however, also be influenced when applying low-e coatings. Modern low-e coatings used for window applications can have emissivity as low as 0.013 [78].

4.1.3 Combined effects – thermal transmittance value

The combined effects of radiation, gas convection and gas conduction for glazing units studied in this thesis have all been calculated according to the algorithms described in ISO 15099 [75]. This is a standard that has historically shown very good correspondence to U-values of windows measured in a large-scale hot box according to the reference standard NS-EN 12567:2010 *Thermal performance of windows and doors – Determination of thermal transmittance by the hot-box method – Part 1: Complete windows and doors* [79].

4.1.4 Energy storage – thermal mass and latent energy storage

Latent thermal energy storage is a mechanism caused by the phase transition of a material. Most common in building applications is the phase transition between the liquid and solid states of a material. Materials used for this purpose are often called phase change materials (PCMs). There is a large potential for energy storage in this phase transition. The latent energy storage of the phase transition is achieved without a significant increase in sensible temperature and provides a higher storage-to-mass ratio efficiency compared to sensible storage only [10].

A PCM layer incorporated in a transparent component can increase the possibility of harvesting energy from solar radiation by reducing the heating/cooling demand and still allowing the utilization of daylight. The PCM is transparent in the liquid state and translucent when in the solid state. The aim of including a PCM layer in a transparent system is to collect (a large part of) the near infrared (NIR) solar radiation (that does not contribute to daylight) within the PCM layer itself and let (the largest part of) the visible solar radiation enter the indoor environment, thus still allowing natural light exploitation for daylighting purposes [58, 59, 66].

4.2 Daylight – Solar gains and visible solar transmittance

4.2.1 Introduction

Solar radiation is made up of three main parts based on wavelength boundary definitions, as shown in Figure 2:

1. Ultraviolet radiation (UV); 300–380 nm
2. Visible radiation (VIS); 380–780 nm
3. Infrared radiation (IR); 380–3000 nm

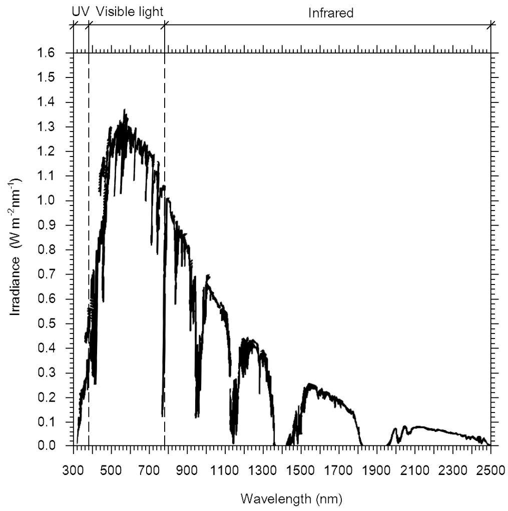


Figure 2. Reference solar spectra for direct normal irradiance and hemispherical tilted irradiance divided in the UV, visible and infrared parts with wavelengths, λ, from 300 nm to 2500 nm [80].

Solar radiation falling on a material will be transmitted, absorbed or reflected depending on incident solar angle, wavelength (λ) and the properties of the material. The solar radiation with a certain wavelength passing through a window is a function of these three processes and is described through the transmittance (τ), absorbance (α) and reflectance (ρ), where the relationship between the three is described in Eq. 4 [35].

$$\tau(\lambda) + \alpha(\lambda) + \rho(\lambda) = 1 \quad (100\ \%) \tag{4}$$

Where:

τ(λ) = Transmittance at wavelength λ
α(λ) = Absorbance at wavelength λ
ρ(λ) = Reflection at wavelength λ

4.2.2 Transmittance factor

The transmittance factor, τ, for a glass pane is a measure of the amount of the incident solar radiation flux which is transmitted through the pane. The transmittance factor may be given for a single wavelength or an integrated value weighted and normalized with the solar spectrum in a specific wavelength section. The integrated value is often denoted as the solar transmittance (T_{sol}) for the whole solar wavelength band and the visible solar transmittance (T_{vis}) for the visible solar radiation located in the 380 to 780 nm waveband [35]; see also 4.2.6.

4.2.3 Absorbance factor

Some of the solar energy hitting a glass pane will be absorbed in the pane itself. This is expressed as the absorbance factor, α, of the glass pane. The absorbance factor may be given for a single wavelength or an integrated value weighted and normalized with the solar spectrum in a specific wavelength section. The integrated value is often denoted as the solar absorbance (α_{sol}) for the whole solar region, for example, the visible solar absorbance (α_{vis}) for the visible solar region [35].

4.2.4 Reflectance factor

The reflectance factor of a surface, ρ, is defined as the ratio of the light flux reflected from a surface related to the incident flux on the surface. The reflectance factor of a glass pane is dependent on the surface properties of the pane and the incident angle of the solar radiation. An untreated pane of float glass has a reflectance for normal incidence close to 0.08 (8 %) when adding the contribution from both glass surfaces of the pane, for example, air/glass and glass/air for a single glass pane. The reflectance factor may be given for a single wavelength or an integrated value weighted and normalized with the solar spectrum in a specific wavelength section. The integrated value is often denoted as the solar reflectance (R_{sol}) for the whole solar region, for example, the visible solar reflectance (R_{vis}) for the visible solar region [35].

4.2.5 Total solar energy transmittance

The total solar energy transmittance (g) is a measure of how much of the incident solar radiation hits the window aperture and is transmitted through to the interior room. It includes both the direct solar transmittance (T_{sol}) and the secondary, absorbed part (q_i) which is re-emitted as thermal (infrared) radiation and convection towards the interior, as shown in Eq. 5 [81]. This is what is defined as the solar heat gain coefficient (SHGC), or solar factor (SF, g-value) for short.

$$g = T_{sol} + q_i \tag{5}$$

Where:

g = Total solar energy transmittance

τ_e = Direct solar transmittance

q_i = Secondary heat transfer towards the inside

4.2.6 Visible solar transmittance

The visible solar transmittance (T_{vis}), also called light transmittance, is calculated for the bandwidth region between 380 and 780 nm as shown in Figure 2. T_{vis} is a specific calculated value which describes the integrated value of the solar radiation which is transmitted through the glazing in that bandwidth region. It is made up of the following three main parts:

1. Direct solar radiation.
2. Diffuse solar radiation from the sky.
3. Diffuse solar radiation reflected from surrounding surfaces.

The general equation for the visible light transmittance is shown in Eq. 6 [81].

$$T_{vis} = \frac{\sum_{\lambda=380nm}^{780\,nm} \tau(\lambda) D_\lambda V(\lambda) \Delta\lambda}{\sum_{\lambda=380nm}^{780\,nm} D_\lambda V(\lambda) \Delta\lambda} \tag{6}$$

Where:

D_λ = Relative spectral distribution of illuminant D65 (see ISO/CIE 10526)
$\tau(\lambda)$ = Spectral transmittance of glazing
$V(\lambda)$ = Spectral luminous efficiency for photopic vision defining the standard observer for photometry (see ISO/CIE 10527)
$\Delta\lambda$ = Wavelength interval

4.2.7 Combined effects – visible and total solar energy transmittance

All of these factors together govern the SHGC and T_{vis} values for an IGU. However, there are some boundaries for how large these values can be in combination. Figure 3 shows calculated values for SHGC and T_{vis} values for a selection of IGUs using non-coated glass panes, absorbing glass panes and low-e coated glass panes using commercially available products. Based on this, a suggested line for the upper theoretical boundary of the combined values is drawn, as showed in Figure 3.

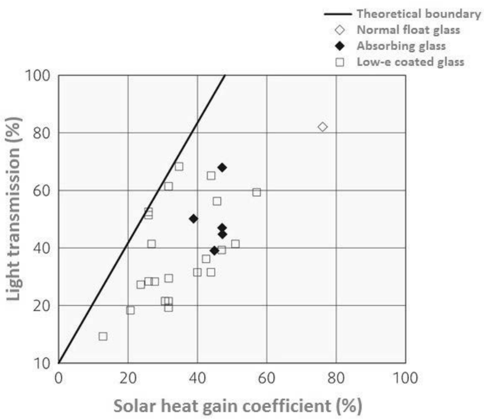


Figure 3. Theoretical boundaries for combinations of SHGC and T_{vis} of IGUs. Values are calculated according to ISO 15099 [76] and ISO 9050[82].

4.3 Performance assessment descriptors

4.3.1 Energy demands

The total heat flow through a window consists of conduction, radiation and convection driven by a temperature difference. Heat transported by conduction, long-wave radiation and convection is in general related to the total U-value of the window. Solar short-wave radiation will also be a large contributor to the heat flow and is related to the SHGC of the window. The general energy transfer equation for a window is given in Eq. 7. Note that the $q_{transmission}$ and q_{sol} terms are directly related to the heating and cooling demands of the building, whereas the $\Delta\xi_{daylighting}$ term is primarily related to a potential decrease in artificial lighting demand, but it will also affect cooling and/or heating demands by reducing internal loads from the artificial lighting. The transmission heat flow, short-wave radiation contribution and the effect it has on artificial lighting demands are accounted for.

$$q_{window,tot} = q_{transmission} - \eta_{shading} \cdot q_{sol} - \Delta\xi_{daylighting} \quad (7)$$

Where:

$q_{window,tot}$	= Total window energy balance	(W/m²)
$q_{transmission}$	= Window transmission heat flow	(W/m²)
$\eta_{shading}$	= Efficiency of shading system	(-)
q_{sol}	= Solar radiation level	(W/m²)
$\Delta\xi_{daylighting}$	= Decrease in artificial lighting demand due to daylight	(W/m²)

4.3.2 Thermal comfort

The notion of thermal comfort is ultimately a qualitative descriptor of the perception of a room. However, a rating scale is often used in order to give a quantitative assessment of the quality. Paper 3 gives a more thorough presentation of the “predicted mean vote” and Fanger scale rating indexes.

In this work, thermal comfort is assessed using the Fanger comfort model [82]. Fanger’s model is based on an energy analysis that accounts for all the modes of energy loss from the body. The model encompasses air and mean radiant temperature along with the applicable metabolic rate, clothing insulation, air speed and humidity to predict thermal comfort. The heat balance is combined with experimentally derived physiological parameters in order to predict the thermal sensation and the physiological response of a person due to their environment. This is quantified here as the Predicted Percentage of Dissatisfied people (PPD). A thorough description of the model can be found in the simulation tool description [83].

A more thorough description of the concept and aspects of thermal comfort are given in paper 3.

4.3.3 Visual comfort – Glare and glare index

The glare index (GI) is, in this context, used to estimate the amount of discomfort glare caused by the windows in an office space. The glare index factor is basically a quantified index which describes the difference between the luminance of an object in relation to the luminance of interior surfaces surrounding the window, as seen from a reference point [84]. Several correlation formulae have been proposed throughout the last forty to fifty years [85].

The discomfort glare index (DGI) is related to set levels of the GI where human perception of the glare takes on different forms. The degree of discomfort is measured in terms of decrement of performance of a given task, corresponding to levels given in NS-EN ISO 12464-1:2011 – *Light and lighting – Lighting of work places – Part 1: Indoor work places* [86].

However, it is important to be aware that there are uncertainties regarding how glare is perceived. This could be caused both by calculation procedures of the DGI as well as differences in human perception of glare [87].

Daylight illumination levels are also an important aspect. In addition to the direct coupling with possible reduction of the need for artificial light, daylight is thought to have beneficial impacts on humans, for example, by improving work efficiency. Nabil and Mardaljevic [88] found, after an extensive literature review, that daylight illuminance levels are beneficial when in the range of 100 to 2000 lux. According to the standard NS-EN 12464-1:2011 [86], the maintained illuminance level for a workspace should be higher than 500 lux.

A more thorough description of the visual comfort concept and the assessments thereof are given in paper 3.

5 METHODS – EXPERIMENTAL DESIGN AND SIMULATION TOOLS

5.1 Methods introduction

This thesis primarily presents research from computer simulations and laboratory experiments. Thus, it differs from the traditional theses published at the Architecture faculty, where qualitative methods are more common. The work presented here is centred on quantitative descriptors used to assess the building performance as a function of window configurations. Some qualitative aspects have, however, been studied. These are related to the thermal and visual comfort of users of the studied office spaces.

This chapter presents an overview of the tools used in the various parts of the thesis. A more detailed description of methods, experimental design and software is given in the respective papers.

5.2 Component-level analysis tools

5.2.1 THERM and WINDOW

THERM and WINDOW software have been the primary analysis tools of the component-level performance. THERM incorporates a two-dimensional heat transfer model, utilizing a finite element method to numerically solve the governing two-dimensional energy flow equations. The details of the models are given in [89].

The WINDOW program was used to assess the centre-of-glazing properties. Fenestration product heat transfer through the centre-of-glazing area is primarily a one-dimensional process. It is analysed by breaking down the glazing system cross section into an assembly of nodes and calculating the heat transfer between each node. WINDOW models the user-defined glazing system as a one-dimensional, steady-state resistance network. An iterative solution method is then used to converge upon the correct temperature distribution. From this temperature distribution, any desired performance index can be calculated.

To accurately model glazing systems with multiple spectrally selective glazings (e.g. glazings with solar-optical properties which vary by wavelength, such as many low-emissivity coatings), a multi-band model is used in WINDOW. In this model, WINDOW calculates the transmittance and reflectance for the glazing layer or the glazing system wavelength by wavelength and then weights the properties by the appropriate weighting functions to obtain the total solar, visible, thermal infrared properties. To use the multi-band model, WINDOW needs a spectral data file for each glazing layer. These data files are updated and maintained by Lawrence Berkeley National Laboratories (LBNL) and are available from the National Fenestration Rating Council (NFRC) [78]. If some of the glazing layers in a glazing system do not have a spectral data file, WINDOW assumes a flat spectral behaviour of the glazings without the spectral data files, based on their stated visible and solar properties [90].

5.3 Building-level analysis tools

5.3.1 SIMIEN

SIMIEN is a tool based on monthly stationary calculations. The algorithms used are described and validated against NS-EN 15265:2007 [70]. The calculations are based on hourly simulation data. SIMIEN was used for an introductory study in paper 1 of this thesis. This software was chosen because it has a well-developed and user-friendly graphical user interface (GUI), and it is a much-used tool among consultants and energy advisors/architects in the Norwegian building industry. However, it has some weaknesses in that there is no representation of the real geometry of buildings and an hourly time-step for calculations is used according to a simplified model in NS 3031 [69]. These issues affected the expected accuracy of the calculation results which led to the decision to switch to a more detailed tool for the remainder of the work. The choice fell on EnergyPlus.

5.3.2 EnergyPlus – BES modelling software

EnergyPlus is an integrated simulation tool. This means that all three of the major parts; building (building envelope), system and plant (zone and air distribution system), are solved simultaneously. The basis for the zone and air system integration is to formulate energy and moisture balances for the zone air and solve the resulting ordinary differential equations using a predictor-corrector approach. Conduction Transfer Functions (CTF) are used for building envelope calculations and are solved using state space methods [84]. The software is flexible and allows for a good representation of integrated simulations of building envelope and HVAC systems in combination. It also allows detailed input of building geometry. There are, however, some drawbacks. Several add-ons have been included since development which has led to a complex programming code and a resulting lack of traceability of the exact code and algorithms used.

EnergyPlus is a commonly used tool which has shown fair correspondence with other similar simulation tools like ESPr and TRNSYS [91]. Accuracy of the software has also been investigated in IEA ECBCS Annex 43 [92]. Simulated values for air temperatures, daylight illumination levels and heating demands were compared to measurements in test office cells with various shading devices and shading control strategies. Estimated values of air temperatures and airflow rates were in general within a 5 % error margin from the measured values. However, prediction of exterior daylight illuminance levels were off by more than 100 % compared to measured values for some cases. This corresponds to findings by Ramos and Ghisi [93]. Subsequently, analyses of daylight distributions and energy demands related to daylight levels in this thesis were carried out using the COMFEN tool.

5.3.3 COMFEN

COMFEN is a graphical user interface using EnergyPlus as the underlying engine for simulations. It is coupled with the Radiance software [94] which is used to render daylight distributions and qualitative assessments through graphical representation of visual comfort and daylight distribution. On the downside, it has some limitations one must be aware of. It has reduced flexibility compared to EnergyPlus as it is only possible to do room-level studies. Choices for HVAC design, strategies and set points are set to default values that cannot be altered. It was, however, found to be suitable for some of the studies carried out in this work based on the beneficial aspects of this tool.

5.4 Laboratory measurements – description of equipment and methods

A full-scale climate simulator, as shown in Figure 4 has been used to assess the thermal and optical performance of a dynamic translucent façade system. A hot box, shown in Figure 4, has been used to measure the thermal transmittance of windows with integrated solar shading devices.

The climate simulator introduces a new way of testing the performance of building components. Temperature controls are coupled with solar radiation stresses using xenon lamps to mimic the spectral distribution of real solar radiation. No governing standards are available for the description of procedures etc. for this apparatus. The climate simulator is described in more detail in paper 4.

Figure 4. Climate simulator (left), hot box (right).

Measurements in the hot box were carried out according to governing standard for window measurements, SO 12567-1:2010 *Thermal performance of windows and doors - Determination of thermal transmittance by the hot-box method - Part 1: Complete windows and doors* [79]. A detailed description of the hot box, relevant measurement standards, procedures and a supplementary discussion relating to estimation of uncertainties are presented in paper 5.

6 RESULTS – SUMMARY OF SCIENTIFIC PAPERS

6.1 Introduction to the papers

Papers 1, 2 and 3 have a strong coherence and are all structured under research part 1 (as discussed in the thesis outline). Office case studies have been carried out where the aim has been to investigate transparent façade optimization possibilities. Varying levels of detail and the inclusion of solar shading devices (or not) make them unique in their own way and they can be read as stand-alone research pieces. However, if one looks at the three in conjunction, a larger picture emerges.

Based on the findings in papers 1–3, a key parameter study of the thermal properties of glazing units was carried out in paper 6. The case studies showed that the thermal properties of the glazing units play a vital role when trying to reduce energy demands in office buildings. Based on this, a choice was made to investigate the possibilities of improving the thermal transmittance values for glazing units. A review of currently available technologies providing low thermal transmittance values was also carried out.

As a supplement to the theoretical studies performed in paper 6, measurements were carried out for two selected technologies in papers 4 and 5. The shading units studied in paper 5 were chosen in order to investigate the possibilities of using in-between pane shading devices to reduce the thermal transmittance of the glazing units when deploying the shading slats. For example, this could be used as night-time shading, when restriction of the view towards the exterior is insignificant.

Paper 4 presents measurements on a novel transparent façade product. For this kind of product, one is moving away from the traditional notion of windows, as the product is no longer transparent and only a translucent appearance is maintained, but it nonetheless shows some interesting properties which should be taken into account. The utilization of thermal inertia in direct coupling with incident solar radiation is a relatively new concept, but the aim is still to reduce energy demands in the buildings in which it is installed. In addition, it has some interesting solar shading properties which are relevant for the studies carried out in papers 1–3.

Summaries of the key findings in the papers are presented in the following sections. The full papers include all results and should be read to get the whole picture and a better understanding of the work carried out.

6.2 Paper 1: Solar Shading Systems and Thermal Performance of Windows in Nordic Climates

A typical office building situated in the climate of Trondheim has been simulated in order to study the effect of various solar shading systems. The building is a three-storey building with a heated floor surface of 3600 m² and a corresponding heated air volume of 10080 m³. The building envelope is made according to the Norwegian building regulations TEK10 [16] with U-values for roof, walls and floor of 0.13, 0.18 and 0.15 W/(m²K), respectively. Air leakages are set to 1.5 h^{-1} and a mechanical, balanced ventilation system with heat recovery is used. The total window area is 20 % of the heated floor surface. A case with two-pane window with U-value = 1.2 W/m^2K and SHGC of 0.55 and a case with three-pane window with U-value = 0.7 W/m^2K and SHGC 0.45 were studied. Simulations were performed for the reference building and various control schemes of the solar shading system.

Figure 5 shows cooling, heating and net energy demand for the case where the windows had a U-value of 1.2 W/(m²K). The effect on cooling, heating and total net energy demands as function of shading strategies and activation fluxes were studied.

As can be seen in Figure 5 and 6, a reduction of window U-values will, as expected, reduce the total energy use of the building regardless of the effect of the solar shading system. It was found that the cooling demand will increase by approximately 10 % as the window U-value decreases from 1.2 to 0.7 W/(m^2K), but the heating demand will be lowered to a greater effect.

The best thermal performance seems to be for the case without shading, although the difference in net energy demand is marginal. The only noteworthy way of reducing the net energy demand is to use windows with a low U-value. However, the simulation tool used for the calculations does not make it possible to investigate the effect of altering the activation flux of the shading system dynamically over an annual cycle.

The simulations show that the control strategy has a significant influence on the resulting cooling, heating and net energy demand. If the operation of the shading system is regulated using erroneous governing procedures, the result might be an increase in total energy demand due to higher total energy use in spite of a reduction in cooling need.

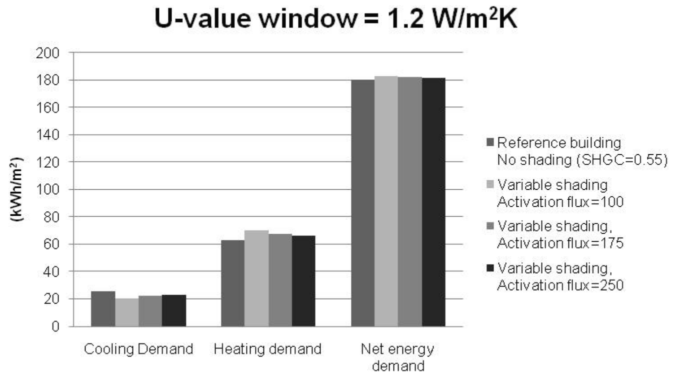


Figure 5. Calculated values for cooling, heating and net energy demand for an office building with two-pane windows. The net energy demand includes energy use for lighting, appliances, etc. in addition to the heating and cooling loads. The shading systems have SHGC values of 0.01 to 0.55 (that of the unshaded window) for the closed and open positions respectively.

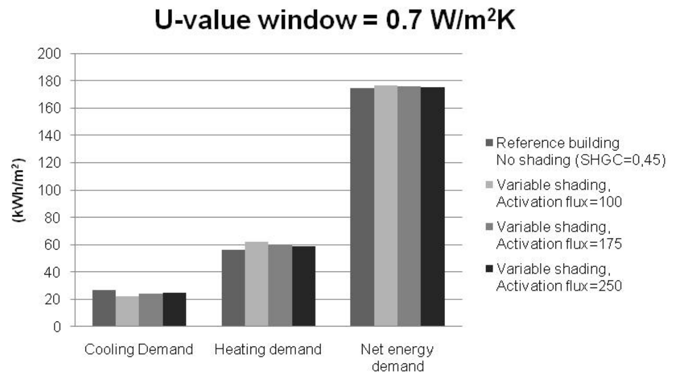


Figure 6. Calculated values for cooling, heating and net energy demand for an office building with three-pane windows. The net energy demand includes energy use for lighting, appliances, etc. in addition to the heating and cooling loads The shading systems have SHGC values of 0.01 to 0.45 (that of the unshaded window) for the closed and open positions respectively.

However, in addition to the factors discussed in this paper, one must study the effects that solar shading has on the energy use related to lighting. The need for artificial lighting will of course increase in line with a reduction in natural lighting.

6.3 Paper 2: Windows in the Buildings of Tomorrow; Energy Losers or Energy Gainers?

This journal paper presents calculations for a range of windows as part of a building where the coupled effects of incident solar radiation and thermal transmission heat losses are accounted for in terms of a net energy balance for the various solutions. Effects of varying thermal transmittance values (U-values) are studied in connection with solar heat gain coefficients.

In this paper, the combined effects of heat loss and heat gains are analysed for a typical Norwegian office building. A parametric study has been performed using the building energy simulation (BES) modelling tool EnergyPlus [95], where the thermal transmittance (U-value) and solar heat gain coefficient (SHGC), also known as solar factor (SF), have been varied arbitrarily to investigate the effects they have on the energy balance of the windows using three distinct rating methods. Three different rating methods, as shown below, was proposed and applied to assess the energy performance of several window configurations.

1. ISO 18292:2011; Energy performance of fenestration systems for residential buildings – calculation procedure [24].
2. The useful gain method
3. The effect on the combined cooling and heating demand of the building.

The application of the ISO 18292 method showed that the windows give a beneficial contribution to the heating demand of the building for most combinations of U-value and SHGC. The useful gains method gave that several U-value and SHGC combinations in theory would reduce the energy demand of the building where the useful energy balance reaches an optimum for a SHGC of 0.4. Similarly, as shown in Figure 7, the combination of a lowest possible U-value and an SHGC value of 0.4 give the lowest combined heating and cooling demand. Figure 7 shows that windows with a U-value lower than 0.4 W/(m²K) and an SHGC below approximately 0.5 will give a net heating and cooling demand lower than for the reference case where windows are replaced with an opaque wall.

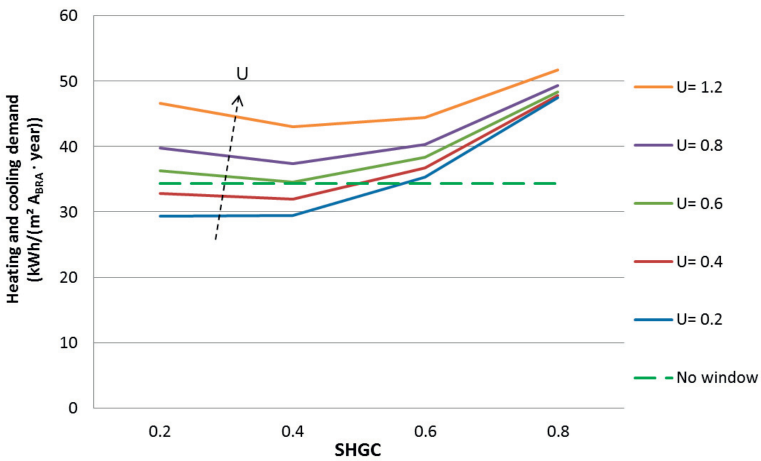


Figure 7. Combined sum of heating and cooling demand for an office building (kWh/(m² A_{BRA} year)) for Oslo's climate. Values from EnergyPlus simulations.

Furthermore, it has been found that windows, even with existing technology, might outperform an opaque wall in terms of heating and cooling demands. Typical state-of-the-art windows available on the market today can reach U-values as low as 0.4 W/(m²K) while still maintaining an SHGC of approximately 0.3, using a four-pane glazing unit. This makes them equal to or even better than highly insulated opaque walls with respect to the total heating and cooling demand. These windows may therefore be classified as *net energy gainers* (for the building studied here).

Table 1 shows a comparison of the energy savings potential ratings using the three methods for three state-of-the-art windows. For the ISO 18292 method, the reference is an adiabatic element, with zero heat loss and zero heat gain, replacing the window. The useful gains method assesses the usability of any solar heat gains that enter via the windows and the useful energy balance of the windows. To ensure coherence with the ISO 18292 method and ease of comparison of results the useful gain is defined as being beneficial in terms of reduction of energy demand. Thus negative values for the useful gains and useful energy balance will give a corresponding reduction of heating and cooling demands

Table1. Comparison of energy savings potential for three windows using the proposed methods.

	Energy demand savings potential (kWh/(m^2 A_{BRA} year))		
	ISO 18292	Useful gains method	Heating and cooling demand*
2-pane window U-value / SHGC = 1.2 / 0.50	-2	12	45 (10)
3-pane window U-value / SHGC = 0.8 / 0.34	-4	4	35 (3)
4-pane window U-value / SHGC = 0.4 / 0.28	-7	-4	32 (-3)

* Figures in brackets show the heating and cooling demand for the window configuration compared to (subtracted from) the heating and cooling demand of the opaque wall reference case. Hence, the four-pane window will act as a *net energy gainer* compared to an opaque wall.

Table 1 demonstrates that the three methods give different energy demand savings potential for all three windows. The difference is largest for the double-pane window, but the discrepancy is still high for the four-pane window. Nevertheless, regardless of method, it was found that a four-pane window will have a beneficial impact on the energy demand compared to an opaque wall.

Furthermore, it was found that a reduction of the window U-value from 1.2 to 0.8 W/(m²K) (e.g. going from a double- to a triple-pane insulated glazing unit) can reduce the energy demand for heating and cooling by 5–15 % depending on the SHGC. Other building configurations may lead to different results.

6.4 Paper 3: Solar shading control strategies in cold climates – heating, cooling demand and daylight availability in office spaces

Simulations of a number of shading strategies was carried out for south- and north-facing office cubicles with varying floor areas, window sizes and window parameters. Two office sizes were studied, one with a heated floor area (A_{BRA}) of 10.5 m² and one with A_{BRA}= 18 m². Energy demands for heating, cooling, lighting and ventilation fans were assessed. Three window-to-wall ratios (WWR) were studied: 41, 51 and 61 %. Three window types were studied; a double pane windows with a U-value = 1.4 W/(m^{2}K), SHGC = 0.48 and visible transmittance (T_{vis}) = 0.71, a triple-pane windows that fulfil the Norwegian passive-house standards [96] with a U-value of 0.7 W/(m^{2}K) SHGC = 0.38 and visible transmittance (T_{vis}) = 0.58 and a state-of-the-art 4-pane window with a U-value of 0.45 W/(m^{2}K) SHGC = 0.28 and visible transmittance (T_{vis}) = 0.48. The opaque part of the façade had a U-value of 0.15 W/(m²K).The simulations show that the choice of shading strategy can have an impact on the energy demand of the offices. Depending on strategy, the energy demand can either increase or decrease compared to an unshaded one- or two-person office cubicle.

The main results of daylight and thermal comfort simulations are shown in Table 2. Best performing shading strategy corresponds to the following; Best performer 1b is the case when shading is activated when internal temperature rises above 26°C and a variable slat angle control is utilized. Best performer 5 is based on a strategy where shading, using fixed slat angle, is activated during night-time if exterior temperature drops below 26°C and activation during daytime if there is a cooling demand present. 5b is identical to 5 with the addition of variable shading slat angles.

Table 2. Key daylight and thermal comfort performance data for south-facing single-person offices with two-pane glazing. The unshaded and the shading alternative with the lowest energy demand for each of the WWRs are shown.

	41 % WWR		51 % WWR		61 % WWR	
	Unshaded	Best performer 1b	Unshaded	Best performer 5b	Unshaded	Best performer 5
Average glare index (GI_{avg})	5	4	5	1	5	1
Hours when glare index > 22	115	113	115	17	115	15
Hours when illumination >300 lux	2613	2476	2926	681	3108	924
Hours when daylight illumination is in the range of 100–2000 lux	3086	2997	2790	1954	2582	1347
Average illumination level due to daylight (lux)	487	462	680	144	904	165
Thermal comfort, Fanger average PPD (%)	18	18	18	21	18	25

North facing office cubicles

North-facing offices were found to have larger energy demands than south-facing offices, mainly due to higher heating demands. Lighting energy demand is also slightly higher for north-facing offices. The use of shading systems has insignificant potential for reduction of energy demands on north-facing façades. On the contrary, it can potentially lead to an increase in energy demands of as much as 5 % if an improper strategy is used. Shading systems should therefore not be used on north-facing façades of small- or medium-sized office cubicles. Using four-pane glazing will, however, reduce the energy demand compared to windows with two- or three-pane glazing. Other aspects such as colour rendering due to a thick glass layer must be addressed in order to ensure good visual quality of the spaces. Using low-iron glass could be one of the technical solutions for this.

The simulations also show that glare issues will never be a problem for north-facing façades. The glare index (GI) level for any of the north-facing façades never exceeded 12.

South facing cubicles

In contrast to the north-facing façades, the results show that there is potential to reduce energy demands for the south-facing façades. Energy demand reductions can be as large as 9 % if the right shading strategy is chosen. However, as for the north-facing offices, it was found that improper use of shading systems will lead to an increase in the total energy demand. This increase in energy demand can be as high as 10 %.

Thus, it can be concluded that automatically controlled shading systems can reduce the energy demands of south-facing, small office cubicles, but they should not be installed without a thorough investigation in each single case.

Upgrading to four-pane glazing will always have a beneficial impact on the energy demand compared to two- and three-pane glazing. Energy demand reductions can be as high as 20 % if two-pane glazing is replaced with four panes. If a three-pane window is interchanged with a four-pane glazing unit, energy demand reductions were found to be as high as 7 %. Glare problems must, however, be addressed and reduced to an acceptable level; this will not be achieved with unshaded façades. The location of glare-reducing measures is not limited to in-between glazing pane shading units; both internal and external shading devices can be utilized.

6.5 Paper 4: Possibilities for characterization of a PCM window system using large scale measurements

Measurements have been carried out on a state-of-the-art, commercially available window that integrates PCMs using a large-scale climate simulator. The glazing unit consists of four-pane glazing with an integrated layer that dynamically controls the solar transmittance (prismatic glass) in the outer glazing cavity. The innermost cavity is filled with a PCM, contained in transparent plastic containers, as shown in Figure 8.

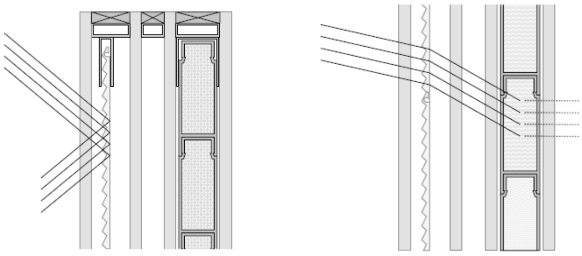


Figure 8. Vertical cross sections of the PCM window. [97]. The figures illustrate the angular properties of the solar reflector in the outer cavity, where radiation with high incidence angles (typical summer days) are reflected and low-angle incident radiation (typical winter days) is let through.

Solar irradiance levels were measured on the interior and exterior sides of the sample, yielding consistent numbers for the amount of radiation transmitted through the sample, regardless of the state of aggregation of the PCM. This value gives one of the components of the SHGC for the system. The value does not, however, take into account the factors of heat transfer due to other transfer mechanisms induced by the effect that the solar radiation has on the surface temperatures and gradients over the sample cross section. These heat transfer effects will be the subject of future studies. It was found that even for temperatures similar to a warm day in the Nordic climate, the potential latent heat storage capacity of the PCM was fully activated. Long periods of sun combined with high exterior temperatures are needed. This suggests that lower melting point temperatures (the system studied had a melting temperature of 26–28 °C) for the PCM could be considered for cold climates to ensure better utilization of the latent heat storage potential The measured surface temperatures of the sample subject to test series with solar radiation of 1000 W/m² and exterior and interior temperatures of 24°C showed the most pronounced effect of the thermal inertia phenomenon and is shown in Figure 9.

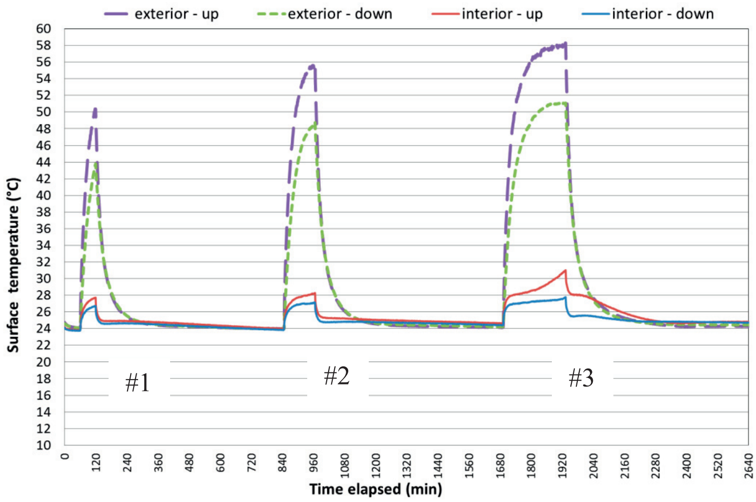


Figure 9. Surface temperature plots for test series 1-3. Solar radiation level 1000 W/m² and interior and exterior temperature 24°C.

The preliminary measurements presented in this paper highlight some important considerations for future experimental research.

The temperature stratification on the window is more significant than expected and is probably related to the highly non-linear behaviour of the PCM layer. The stratification is enhanced by the fact that in some areas the PCM completes the melting process, while in others it stays in a solid-liquid mixture during the whole test. This makes it necessary to measure the surface temperature in several places in order to have a full picture of the window's thermal behaviour.

The very high thermal inertia of the system prevents it from reaching a steady-state condition if only 12 hours are left between two solar stimuli; this phenomenon is especially enhanced when solar stress and thermal gradient stress are combined. Thus, in future analyses, longer relaxation periods need to be employed, namely at least 24 hours.

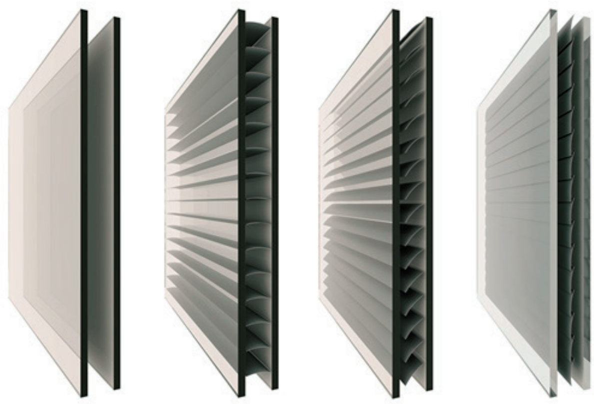
A limitation in the study relates to the solar simulator structure. It is not able to replicate the full optical characteristics of solar irradiance (i.e. direct component plus indirect irradiance). Due to the particular technology under investigation, prismatic glass, which has a high dependence on the geometry of the solar radiation, it is only possibly to complete partial measurements. Unfortunately, it is not possible to solve this issue with the available test rig. In order to overcome this limitation, a measurement study using an outdoor test cell facility is planned.

6.6 Paper 5: Thermal performance of in-between shading systems in multilayer glazing units – Hot-box measurements and numerical simulations

This journal paper included hot-box measurements of thermal transmittance values (U-values) performed for three insulated glazing units with integrated in-between pane shading systems. The shading devices are venetian-type blinds with horizontal aluminium slats. The windows with double- and triple-pane glazing units have motorised blinds. The shading device is placed in the exterior cavity of the triple-pane glazing. The window with four-pane glazing has a manually operated blind placed in an external coupled cavity. The measurements were compared to numerical simulations using the WINDOW and THERM simulation tools developed at the Lawrence Berkeley National Laboratories.

The uncertainties associated with the hot-box measurements were assessed in accordance with the procedure described in ISO 12567-1:2010 [79]. The total uncertainty propagation of the measured U-values, $\Delta^P U_w/U_w$, were derived using the root-mean-square method (RMS). The uncertainty in the sample heat flow was based on the heat balance equation for the metering chamber. The uncertainties stated in this work are given with a coverage factor of two standard deviations and the corresponding 95 % confidence interval.

The aim of the study was to assess the effect of operating the blinds on the U-value of the windows. The U-values as a function of various slat angles and blind positions, as shown in Figure 10, were studied. In the paper, both centre-of-glazing U-values and whole window U-values were measured.



1 2 3 4

Figure 10. Shading slat angles and position configurations illustration,numbers indicating; 1 the blinds fully retracted, 2 the blinds down and the slats in an open (horizontal, α = 0°) position, 3 blinds down and the slats in α = 45° position (for the 4-pane window), 4 blinds down and the slats in a closed (vertical, α = 90°) position.

The measured mean U-values for the windows with closed blinds with horizontal slats were unaffected for the window with the 2-pane IGU. The U-value of the 3-pane IGU window was increased by 3 % compared to retracted (open) blinds, whereas the U-value of the window with the 4-pane glazing unit was increased by 1 %.

The measured mean U-values for the windows when closing the blinds with vertical slats were reduced by approximately 3 % for the windows with the 2- and 4-pane glazing unit compared to retracted (open) blinds. The mean U-value of the window with the 3-pane glazing unit was reduced by 1 %.

Shading systems like this are considered by some to be an effective system for reducing the U-values of the glazing units when they are closed. Based on the measurements carried out in this work, it can be concluded that shading devices with properties like the ones measured should not be considered as an effective system for reducing the U-values of windows. The measured and calculated values are shown in Figure 11. The figure shows the U-value on the vertical axis for the 10 different measurement configurations, as described in Table 3, on the horizontal axis.

Table 3. Measurement series description.

Test series ID	Test series description
1	2-pane glazing with retracted (open) blinds
2	2-pane glazing with deployed horizontal blinds (closed blinds with horizontal slats)
3	2-pane glazing with deployed vertical blinds (closed blinds with vertical slats)
4	3-pane glazing with retracted (open) blinds
5	3-pane glazing with deployed horizontal blinds (closed blinds with horizontal slats)
6	3-pane glazing with deployed vertical blinds (closed blinds with vertical slats)
7	4-pane glazing with retracted (open) blinds
8	4-pane glazing with deployed horizontal blinds (closed blinds with horizontal slats)
9	4-pane glazing with blinds in 45° position (closed blinds with slats in 45° angle)
10	4-pane glazing with deployed vertical blinds (closed blinds with vertical slats)

Similar trends for the measured values were found in the calculated values. With the exception of the window with the 2-pane IGU, minor reductions in the U-values of the windows were found when closing the blinds.

Simulations showed that the instalment of a shading device in the gas-filled cavities of the 2- and 3-pane IGUs will increase the U-value of the glazing units. The protruding aluminium components of the shading device motor as well as the venetian blinds themselves act as thermal bridges. For the 2-pane IGU, the U-value of the window was found to decrease by approximately 12 % from 1.57 to 1.42 W/(m²K) if the shading device and motor were removed. Thus, any beneficial effects expected to be achieved by using the venetian blinds as an additional layer in the IGU were found to be counteracted by the thermal bridging. The U-value of the window is less affected when removing the shading device motor and the shading blind itself for the windows with 3- and 4-pane glazings. A U-value reduction of 6 %, from 0.79 to 0.75 W/(m²K), was found for the window with a 3-pane IGU. The U-value of the window with the 4-pane glazing unit is reduced by only 2 %, from 0.654 to 0.647 W/(m²K).

The numerically calculated values were in general found to be lower than the measured values. The reasons for this can be many. Firstly, the actual low-e coatings can be of a poorer quality than what the declared values are stated as. Secondly, even though the pressure difference across the windows (i.e. pressure difference between the warm and cold chamber of the hot box) were found to be close to zero at the start and end of the measurement periods, some air leakages could have occurred during the measurement periods. This will contribute to a higher heat flow from the warm to the cold side. This increase in heat flow contributes to a higher U-value of the window. Thermal bridging effects, other than the ones discussed in relation to the shading devices, could also be a contributing factor for the modelled values being lower than the measured U-values.

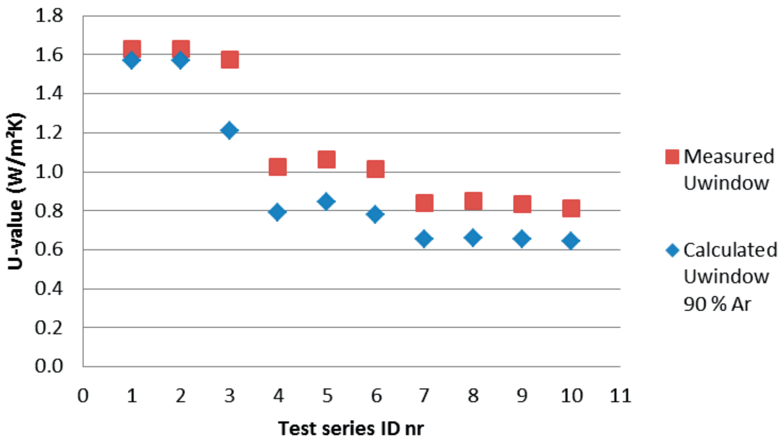


Figure 11. Comparison of measured and calculated mean U-values of whole windows, U_{window}.

In order to achieve more effective shading devices, several factors should be explored:

- Redesign motors in order to minimize protruding aluminium from the cold to the warm side.
- Reduce slat thermal conductivity in order to reduce thermal bridging effects.
- Improve surface properties of slats (e.g. reduce emissivity) in order to reduce radiative heat loss from the warm to the cold side.
- Improve airtightness of shading layer by reducing openings between slats when in the closed position and by making tight connections towards the edges of the cavity.

6.7 Paper 6: Multilayer Glazing Technologies: Key Performance Elements and Future Perspectives

In this study, numerical studies have been carried out with the aim of identifying the key parameters in improving thermal performance of multilayer glazing units. A survey of interesting new products and application cases is also presented.

Figure 12 shows calculated centre-of-glazing U-values on the vertical axis, as function of number of glass panes along the horizontal axis of. The upper left figure shows the effect of varying the cavity thickness of the IGUs. The upper right shows the effect of reducing glass-pane surface emissivity values. The lower figure shows the effect of reducing the gas thermal conductivity of the cavity gas-fillings.

It has been found that increasing the number of glass panes in the insulated glazing units (IGUs) yields U-value reductions that decrease for each added glass pane. Furthermore, improving the low-emissivity surface coatings of panes in an IGU yields little possibility for improvement compared with today's state-of-the-art technologies. Cavity thicknesses between 8 and 16 mm were found to be optimal for IGUs with four or more panes. Reducing the gas thermal conductivity was found to have the largest impact on the U-value. The effect, however, gets less pronounced with an increased number of panes in the IGUs.

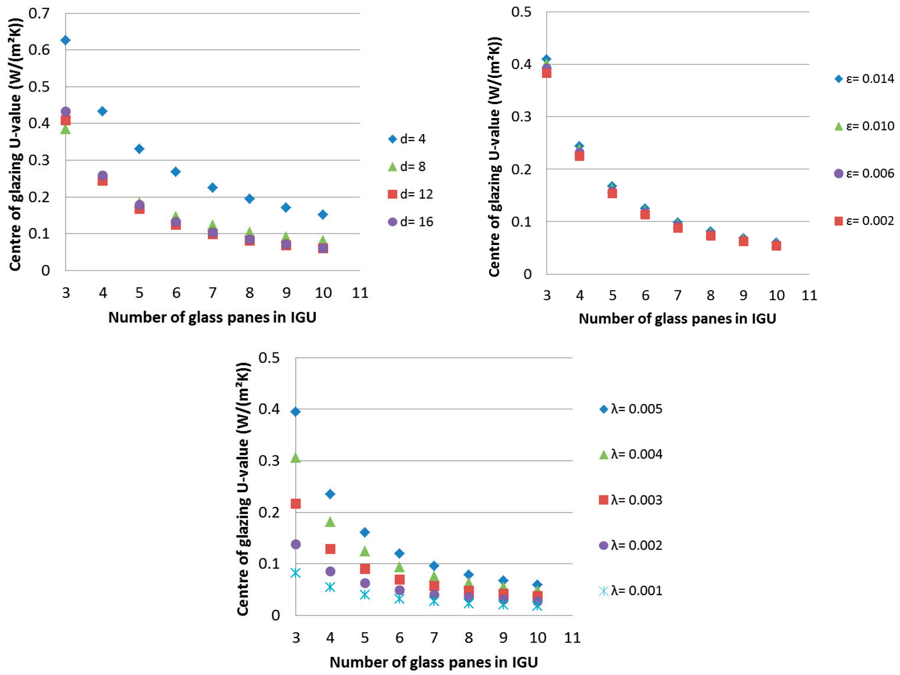


Figure 12. Top left shows U-values for the centre-of-glass as a function of the number of glass panes for different cavity thicknesses (d = 4, 8, 12 and 16 mm). Top right shows U-values for the centre-of-glass as a function of the number of glass panes for different

emissivity of the reverse side (i.e. the surface facing the interior) of each glazing layer. Bottom graph shows U-values for the centre-of-glass as a function of the number of glass panes with different gas thermal conductivities.

Further research should be coupled with life cycle assessments to consider if the optimal number of panes is the same when embodied energy is also accounted for. Further improving the low-e surface coatings of panes in an IGU yields little improvement possibilities compared with today's state-of-the-art technologies ($\varepsilon \approx 0.013$).

In addition to the thermal performance of the glazing units, optical properties, aesthetics, ageing properties and robustness should be further studied before the use of such multilayer IGUs may be recommended. Preliminary numerical simulations have demonstrated that thermal stresses to the glazing units due to high cavity temperatures can pose a problem for the robustness and lifetime of the glazing units. However, the reliability of these results should be treated with caution and further studies and validation experiments of the algorithm used in the software should be carried out.

Further studies should be carried out keeping the following factors in mind:

- Improve solid materials (e.g. lower thermal conductivity and/or weight of glass or polymer layers).
- Geometry of intermittent layers.
- Reduce weight without compromising the performance.
- Prevent/slow the ageing processes.
- Reduce/prevent temperature peaks in central layers.

6.8 Main findings in papers

The conclusions from the work carried out in the six papers are discussed in the scientific papers and a summary of each paper is given in sections 6.2–6.7. The main findings are summarized below categorized according to building-level performance and component-level performance.

Building level

- The results from the simulations show that cooling demands can be dominant in office buildings even in what is commonly considered to be a heating-dominated cold climate like Oslo in Norway.
- Typical state-of-the-art windows, with 4-pane insulated glazing units (IGUs), available on the market today are equal to or even better than highly insulated opaque walls with respect to the total heating and cooling demands in the office building studied. Upgrading to state-of-the-art 4-pane glazings will always have a beneficial impact on the energy demand compared to 2- and 3-pane glazings. However, other building configurations may lead to different results.
- Low window thermal transmittance values (U-values) combined with solar heat gain coefficients (SHGC) of 0.4 are desirable in cold climates.
- Using such state-of-the art windows gives architects and designers greater flexibility in terms of altering window areas and at the same time maintaining good energy performance of the building.
- The introduction of controllable solar shading systems is vital to reducing the energy demands further than what is possible with unshaded windows, if controlled correctly.
- The choice of shading control strategy can have significant impacts on the energy demand of offices.
- Automatically controlled shading systems can reduce the energy demands of south-facing, small office cubicles, but they should not be installed without a thorough case-by-case investigation. It was found that improper use of shading systems will lead to an increase in the total energy demand. Depending on shading strategy, the energy demand can either increase or decrease compared to an unshaded one- or two-person office cubicle.

Component level

- Further improving the low-e surface coatings of panes in an IGU yields almost no improvement compared with today’s state-of-the-art technologies.
- Cavity thicknesses between 8 and 16 mm were found to be optimal for IGUs with four or more panes. Cavities should be kept at 8 mm in multilayer IGUs in order to keep the total thickness of the IGU as thin as possible.

- Reducing the gas thermal conductivity was found to have the largest impact on the U-value. The effect gets less pronounced with an increased number of panes in the IGUs.
- Increasing the number of glass panes in the IGU yields U-value reductions that decrease for each added glass pane. Further research should be coupled with life cycle assessments in order to investigate the optimal number of panes when the embodied energy of the windows is also included and accounted for.
- Preliminary numerical simulations have demonstrated that thermal stresses to the glazing units with multiple layers due to high cavity temperatures can pose a problem for the robustness and lifetime of such units.
- Measurements have been carried out in order to investigate U-values of windows with 2-, 3- and 4-pane glazing units with integrated (in-between pane) venetian-style shading units placed in-between the panes of the interior cavity of the IGU.
- The measured mean U-values for the windows when closing the blinds with vertical slats are reduced by approximately 3 % for the windows with the 2- and 4-pane glazing unit compared to retracted (open) blinds. The mean U-value of the window with the 3-pane glazing unit is reduced by 1 %.
- Any beneficial effects expected to be achieved by using integrated venetian blinds as an additional layer in the IGU were found to be counteracted by the thermal bridging of the shading hardware. The instalment of a shading device in the gas-filled cavities of the 2- and 3- pane IGUs will increase the U-value of the glazing units by as much as 12 %.
- Shading devices with properties like the ones measured should not be considered as an effective system for reducing U-values of windows.
- A novel façade component incorporating phase change materials (PCMs) was measured, and it was found that even for temperatures similar to a warm day in the Nordic climate, the potential latent heat storage capacity of the PCM was able to be activated and utilized. However, long periods of sun (solar radiation) and high exterior temperatures are needed. This suggests that lower melting point temperatures (the system studied had a melting temperature of 26–28 °C) for the PCM could be considered for cold climates to ensure better utilization of the latent heat storage potential.

7 DISCUSSION AND CONCLUSIONS

7.1 Windows and glazed façades in office buildings

Papers 1–3 focused on how the design of the glazed parts of the building influences the energy demand of the building in connection with assessments of thermal and visual comfort in the selected sample building and office cells.

One of the main results from the simulation work is that cooling demands are becoming a dominating factor in office buildings with well-insulated envelopes, even in what is commonly considered to be a heating-dominated cold climate like Oslo in Norway. Hence, it is important that the design of the window and glazed façades used in such buildings takes into account not only thermal properties, but also optical properties related to solar insolation. Low window U-values combined with an SHGC close to 0.4 were found to be the optimum for the sample office building situated in a cold (Oslo) climate using three different rating methods. This ensures an optimal balance where as much as possible of the useful solar gains are harvested while, at the same time, the solar gains that lead to cooling demands are kept at a minimum.

In retrospect, it can of course be argued that these results are valid only for the single office typology studied for one specific climate. However, recent studies that looked at the effect of the building geometry showed that, for example, varying the size of windows had little effect on heating, cooling and artificial lighting demands [10]. This might imply that using the results obtained in papers 1–3 will have a more generic validity.

The debate related to the introduction of the passive house concept in Norway has been coloured by a certain disregard for windows. It has been a common perception that window areas should be minimized in order to reduce the energy demand of passive houses. However, modern windows can perform well in low- or zero-energy buildings. Windows with 4-pane IGUs will be equal to or even better than highly insulated opaque walls (i.e. equal to passive house standard insulation level) with respect to the total heating and cooling demands in the sample office building. As a result, it could be possible to move away from passive houses with small window areas by using state-of-the-art windows, thus expanding the flexibility in the architecture, design and layout of future low-energy, nearly-zero or zero-energy office buildings.

It should also be mentioned that the Norwegian building regulations only focus on the thermal transmittance of windows and not the solar gains and visible transmittance in an explicit way. Future regulations should be clearer in addressing these aspects when both thermal and visual conditions are considered.

Thus, it becomes obvious that modern buildings and the demands of its users make shading devices necessary in order to maintain visual and thermal comfort and also to reduce cooling demands during certain periods of the year. The introduction of controllable solar shading systems is therefore vital to reducing the energy demands; however, such shading devices should not be used without careful planning.

The shading control strategy can have significant impacts on the energy demand of offices. Depending on strategy, the energy demand can either increase or decrease compared to an unshaded one- or two-person office cubicle. Potential for reduction of energy demands was found for south-facing office cubicles. Energy demand reductions can be as large as 9 % if the right shading strategy is chosen. Furthermore, it was found that the improper use of shading systems will lead to an increase in the total energy demand. This increase in energy demand can be as high as 10 %. Hence, it was found that the wrong use of shading systems will lead to an increase in the total energy demand. This is caused by the fact that the wrong shading strategy will block more of the beneficial solar gains than the unwanted solar gains leading to cooling demands. Seasonal shading control strategies could perhaps be considered to a larger degree. In addition, glare problems must be addressed and reduced to an acceptable level; this will not be achieved with unshaded façades. The location of glare-reducing measures is, however, not limited to in-between glazing pane shading units. Both internal and external shading devices can be utilized.

The ability to simulate shading control strategies should be better integrated in building simulation tools. The simulation results for thermal comfort found in paper 3 of this work were ambiguous and should therefore be treated with care. Further investigation of simulation models and procedures should be carried out. Measurements of component performance as well as room- and whole building-level performance should be carried out with validation of simulation tools as one of the objectives. Making tools more precise and easier to use might lead to wider adoption of the tools and (hopefully) in turn give better predictions of energy demands and user perception of future buildings.

7.2 Window component performance

Improving the energy performance of windows should not be seen as an exercise in adding more and more layers to the IGUs, even though a building's total energy demand reductions can be as high as 20 % if 2-pane glazings are replaced with 4-pane glazing units, as found in paper 2. Likewise, if a 3-pane unit is interchanged with a 4-pane glazing unit, total energy demand reduction was found to be as high as 7 %.

A major argument against multi-pane IGUs (with four or more layers) is that the weight will increase and make transport, handling and mounting of windows impractical or impossible in addition to extra loads on the load-bearing structure of the frame and surrounding structure. Also, visible solar transmittance will be reduced and the inhabitants' visual perception of the IGUs will likely be impaired. In paper 6, it was concluded that the only practical way of reducing the thermal transmittance of IGUs without adding additional glazing layers is to reduce gas thermal conductivity. This could be achieved by reducing the gas pressure in the cavities and thus moving towards vacuum glazing. Another alternative to improve thermal properties is by adding glass layers while at the same time trying to keep the weight of the units low. Using thinner glass layers is a possible solution to this. However, for the layers to be effective, it is vital that the beneficial surface properties from the traditionally low-emissivity coated glass panes are kept. This leads to challenges for extremely thin glass layers with thicknesses as low as 0.1 mm, as discussed in paper 6.

In paper 5, measurements and simulations were carried out in order to investigate U-values of windows with 2-, 3- and 4-pane glazing units with integrated (in-between pane) venetian-style shading units. The aim of the study was to assess the effect of operating the blinds on the U-value of the windows. The U-value as a function of various slat angles and blind positions was studied. The significance of these reductions was found to be in the magnitude of 1 to 3 %, making it marginal from a global perspective. Taking into account the thermal bridging effects formed by the shading devices themselves, there are even fewer benefits to this system if the aim is to reduce the thermal transmittance value of the windows. Any beneficial effects expected to be achieved by using integrated venetian blinds as an additional layer in the IGU were found to be counteracted by the thermal bridging of the shading hardware. The instalment of a shading device and motor in the gas-filled cavities of the 2- and 3-pane IGUs will increase the U-value of the glazing units by as much as 12 %.

Hence, shading devices with properties like the ones measured (with aluminium slats) should not be considered as an effective system for reducing the U-values of windows. However, several actions could be taken to improve the efficiency of the shading devices.

Another strategy for reduction of energy demands and improvement of comfort in buildings is through the use of thermal mass. A study was carried out where the thermal mass is coupled with a transparent façade element. The element encompasses a layer of phase change material together with a solar shading device in a four-layer glazing unit. The results showed that the latent heat storage capacity of the PCM layer was utilized during a climatic load similar to that of a Norwegian summer day. Beyond this, further studies need to be carried out in order to understand and describe the full effects that such a system has on the energy demand and comfort in an entire building compared to that of traditional windows. However, these studies have given results that indicate that the methods used for characterization of the transparent façade element are relevant and that the results form a good base for further studies of such technologies.

8 FUTURE WORK

The investigations carried out in this work assess the operational energy performance of windows in energy-efficient, low-energy, nearly-zero or zero-energy office buildings. The results form a decision base which can be used for further life cycle assessments (LCA).

Future studies should include investigation of shading systems placed in the outermost or any other than the inner cavity of the glazing units as well as externally positioned shading systems. Four-pane glazings in combination with in-between or external shading systems should also be further studied. Studies should include implementing controllable solar shading systems and the effect of solar radiation on the heating and cooling demands as well as on artificial lighting demand through studies on the whole building level. State-of-the-art systems and control strategies for these should be investigated numerically and experimentally. Optimization of thermal and optical performance of glazed façades with and without shading systems should be sought in order to make guidelines useable in the early stages of planning offices and office façades.

Glare effects and comfort should also be included to give a better understanding of how the transparent façades in combination with shading systems affect not only thermal performance, but also both the thermal and visual comfort in low- or zero-energy office buildings. The simulation results for thermal comfort carried out in this work were ambiguous and should therefore be treated with care and further investigations of simulation models and procedures should be performed.

New technologies for lighting (LED lighting) and technical equipment producing less heat are developing rapidly. This influences internal gains for office buildings even more. The effects of a reduction on cooling and heating demand should be further investigated.

Measurements of component performance as well as room- and whole building-level performance should be carried out where the outcome should also include validation of simulation tools.

There is an extensive need for further component-level research regarding IGUs. Essential topics are; improved solid materials (e.g. lower thermal conductivity and/or weight of glass or polymer layers), the geometry of intermittent layers, robustness (ageing) and temperature strains.

Future research on shading devices should include optimization of the shading device and motors in order to minimize the protruding aluminium from the cold to the warm side, for example, by reducing slat thermal conductivity in order to reduce thermal bridging effects and improve the surface properties of slats (e.g. reduce emissivity) in order to reduce the radiative heat loss from the warm to the cold side. Further research should also focus on using shading devices as a possibility for night-time insulation. An improved airtightness of the shading layer by reducing openings between slats when in the closed position and by making tight connections towards the edges of the cavity is one way ahead.

Lastly, further studies should be carried out on phase change material behaviour in windows and transparent parts. The effect on the building’s overall energy demands as well as in thermal and visual comfort levels have to be further explored.

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10 APPENDICES – SCIENTIFIC PAPERS IN FULL

1. S. Grynning, A. Gustavsen, and B. Time, "Solar Shading Systems and Thermal Performance of Windows in Nordic Climates", *9th Nordic Symposium on Building Physics*, Tampere, Finland, 29 May–2 June 2011.

2. S. Grynning, A. Gustavsen, B. Time, and B.P. Jelle, "Windows in the buildings of tomorrow; Energy losers or energy gainers?", *Energy and Buildings*, 61, 185–192, June 2013.

3. S. Grynning, B. Time, and B. Matusiak, "Solar shading control strategies in cold climates – Heating, cooling demand and daylight availability in office spaces", *Solar Energy*, 107, 182–194, 2014.

4. S. Grynning, F. Goia, E. Rognvik, and B. Time, "Possibilities for characterization of a PCM window system using large scale measurements", *International Journal of Sustainable Built Environment*, 2, 56–64, 2013.

5. S. Grynning, C. Misiopecki, S. Uvsløkk, B. Time, and A. Gustavsen, "Thermal performance of in-between shading systems in multilayer glazing units – Hot-box measurements and numerical simulations", accepted for publication in *Journal of Building Physics*, 10.10.2014.

6. S. Grynning, B.P. Jelle, A. Gustavsen, T. Gao, and B. Time, "Multilayer Glazing Technologies: Key Performance Parameters and Future Perspectives", submitted for publication.

Scientific paper I

Steinar Grynning, Arild Gustavsen, and Berit Time

Solar Shading Systems and Thermal Performance of Windows in Nordic Climates

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Solar Shading Systems and Thermal Performance of Windows in Nordic Climates

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KEYWORDS: *Glazing, solar shading, shutters, U-value, heating demand, cooling load, control*

SUMMARY:
Buildings account for a significant part of the energy use and greenhouse gas emissions. Therefore one has to improve the energy efficiency of buildings. The most effective action for further reduction of energy loss through the building envelope is to optimize the window area and position for minimum heat loss and optimal solar gains.

A typical office building situated in Trondheim climate has been simulated in order to study the effect of various solar shading systems. The simulations have been performed for the reference building using various control schemes of the shading system.

It is vital that one does not optimize the performance of single components or systems in the building without looking at the building as a whole system that interacts closely. The simulations presented in this article do not take into account the effect on artificial lighting needs, and variations in internal gains.

The simulations show that the control strategy seem to have a significant influence on the resulting cooling-, heating and net energy demand. If the operation of the shading system is regulated using erroneous governing procedures the result might be an increase in total energy demand due to a higher total energy use in spite of a reduction in cooling need

In addition to the factors discussed in this article, one must however study the effects solar shading has on the energy use related to lighting, The need for artificial lighting will of course increase in pace with a reduction in natural lighting accessibility.

In the buildings of tomorrow it is probable that we will see a reduction of energy use for lighting (i.e with the introduction of LED lighting). In addition energy use for TV-screens computers and such appliances could also be reduced in the future, thus reducing the internal gains in the building. These factors will also influence the effect and operation of any installed solar shading.

1. Background

Buildings account for a significant part of the energy use and greenhouse gas emissions. Therefore one has to improve the energy efficiency of buildings. Concepts like passive houses and zero emission buildings are being introduced. Increased thermal performance of the building envelope is a common denominator for these buildings of tomorrow. In order to optimize the building envelope one has to consider the different envelope parts and identify the key critical performance parameters for each. Based on this one can determine which parts of the building envelope that has the biggest potential for energy savings.

The most effective action for further reduction of energy loss through the building envelope is to optimize the window area and position for minimum heat loss and optimal solar gains. The heat loss through the windows constitutes roughly 30 % of the total building heat loss for a typical office building in Norway. The total heat loss distribution for this building is shown in Figure 1.

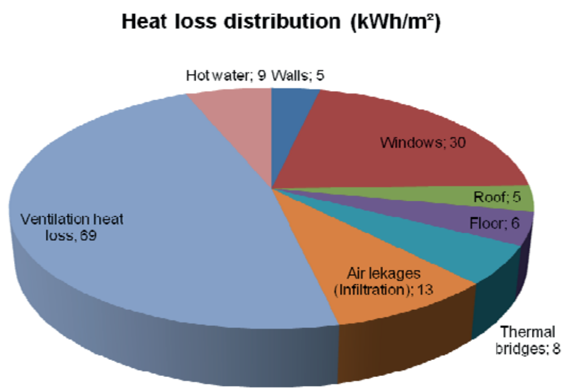

FIG 1. Heat loss distribution (in kWh/(m^2 year)) for a typical office building in Norway, built after the Norwegian building codes. (Grynning et.al 2011)

One of the aims for the future is to develop solutions for day-lighting and solar shading systems that reduce energy use for heating, lighting and cooling and that provide a high quality indoor nvironment. The solutions are to be appropriate for cold climate zones.

2. Solar shading systems

When it comes to controlling or altering the thermal- as well as the light transmission properties and performance of a facade, one has several principle ways of controlling this performance. The traditional way of altering the amount of- and distribution of incident solar radiation is done using *solar shading systems*. In this context one could easily consider this as a low-tech alternative, but it might nevertheless be effective alternatives. In the field of solar shading, there exist primarily three main types of shading; internal-, external- and in-between-pane shading systems. In order to assess the performance of these systems one has to consider a range of factors. Laouadi (2010) suggest a list of *performance metrics*

- Light Diffusion Index (HAZE)
- Visible Transmittance (TVIS)
- UV-Transmittance (TUV)
- Fading Transmittance (TFD)

- Skin Damage Transmittance (TSD)
- Solar Heat Gain Coefficient (SHGC)
- Thermal Transmittance of glazing assembly (U-value)
- Thermal Transmittance of edge-of-glazing (U-value edge)
- Luminance Index (LI)
- View-Out Index (VOI)
- Moisture Condensation Indicator

In addition to this list, the authors strongly suggest that one should also include architectural quality as a separate and equally important performance meter. One might dispute the architectural qualities and how successful the integration is of an exterior roll shutter system as shown in Figure 2. However, this discussion does not fall unto the scope of this article.

FIG 2. Exterior roll shutter system (Laouadi, 2010).

In the following, only performance related to the thermal transmittance (U-value) and the Solar Heat Gain Coefficient (SHGC) will be addressed.

2.1 Internal shading systems

The most common type of slat blinds are that of venetian blinds with horizontal or vertical blinds. The effect of this type of shading depends on several factors like the conductivity of the blinds, slat angle, emissivity of surfaces and geometrical design. All of these factors complicate calculations. ISO 15099 (2003) presents a detailed method for calculating thermal performance of windows, doors and shading systems.

Curtains are the typical shading device used in single family dwellings and they are mainly used to prevent visible access from the outside and to prevent glare. The effect on heat loss is relatively small. The same can be said about shading devices like roller shutters and similar.

Internal solar shading systems has in general been assumed to have a limited influence on the thermal transmittance through glazed facades with low U-values, i.e. the U-value is not influenced in a noteworthy manner (Laouadi, 2010). However, measurements using a hot box indicated that by mounting blinds to the window the effective U-value of a double-pane glazing system was reduced by approximately 5 % compared to the un-shaded window (Fang, 2001). Measurements done by Fang (2000) confirm that an increase in the reflectivity of the (Venetian) blinds will reduce the effective U-value of the glazing system further. The effect will nevertheless be smaller than for an external shading system (Laouadi, 2010).

Depending on the reflective properties of the shading system surfaces, superfluous heat may be radiated back through the glazing, thus giving a potential for a reduced cooling demand. Laouadi (2010) estimates the potential energy savings related to cooling to be approximately 15 % for small windows (0.6 m wide and 1.5 m high) using high reflectance blinds.

The main reason for using internal solar shading should therefore be to control glare and to some extent the visible light transmission through the glazed area. If the aim is to reduce U-values and heat loss other positions should be considered.

2.2 In between pane shading systems

One of the benefits of in between pane shading systems is the potential effect on the U-value of the glazing system. If the system is constructed in an optimal way, the shading screen may act as an additional layer of the glazing system, i.e. a two-pane glazing will, in some limited manner act as a three-layer glazing. Rosenfeld et.al (2001) presents results from both calculations and measurements that show a potential for reducing the total solar energy transmission by approximately 30 % for a double-layer glazing system, depending on the angle of the lamellae in the blind and angle of incident solar radiation. However, Laouadi (2010) concludes that slat-type shading made of metal might introduce substantial thermal bridges thus increasing the U-value. Furthermore Laouadi concludes that the use of plastic as the slat material, the U-value of two- and three-pane glazings may be reduced by as much as 20 %. Measurements performed on a two-pane glazing system indicates that the U-value could be reduced from 1.2 W/m^2K to 0.8 W/m^2K by mounting an airtight solar shading screen inside the gas filled cavity, acting as a third pane of glass in the closed position (Pellini Industries, 2010)

2.3 External shading systems

Detailed calculations for solar transmittance through exterior slat type blinds are, in the same way as for interior placed slat type blinds, complex calculations. Several studies have been performed where factors like slat-geometry, angle and emissivity of surfaces have been implemented in the calculation methods. The effect the albedo of the surrounding surfaces has on the transmitted energy (g-value) has also been discussed in some studies (Simmler and Binder, 2008). As for the internal shadings, screen shadings and roller blinds might also be applicable for an external shading system.

2.4 Shading systems summary

In general, it is concluded that external shading devices perform better than internal shading devices. (Rosenkrantz, 2003).

To function properly the internal shading needs to be highly reflective in order to reflect the heat effectively back out through the window/glazing area. However the rather small relative effect of internal shading will decrease even more as the insulating performance of the glazing increases. In conclusions this means that externally placed shading systems might be even more interesting in the zero emission buildings of the future, where the U-value of the windows is low.

Poirazis (2005) and Poirazis et.al (2007) has done energy simulations for an extensive amount of different glazing and solar shading solutions for an office building in Sweden. The results presented indicate that there is indeed an energy savings potential affiliated with the use of shading systems. The effect of the solar shading on the thermal performance depends on the glazing system area and U-value. If the U-value decreases, the effect of the solar shading system will also decrease. Future buildings must however make use of windows with lower U-values than the ones used in the calculations performed by Poirazis (2005) and Poirazis et.al (2007).

3. Energy use calculations

3.1 Calculation method

In order to further assess the energy savings potential for various shading systems, calculations have been performed using the calculation program SIMIEN (Programbyggerne, 2011). Total energy use and cooling demand has been calculated for a base-concept office building that fulfils the Norwegian building regulations (TEK10, 2010). Further calculations have been performed to investigate the end energy use effect of various solar heat gain coefficients (SHGC), number and areas of windows and different set-points for control of variable solar shading.

3.2 The building

A typical office building situated in Trondheim climate has been simulated in order to study the effect of various solar shading systems. The building is a three storey building with a heated floor surface of 3600 m^2 and a corresponding heated air volume of 10080 m^3.The building envelope is made according to the Norwegian building regulations TEK10 (TEK10 2010).This gives U-values for roof, walls and floor equal to 0.13, 0.18 and 0.15 W/m^2K, respectively. Air leakages are set to 1.5 h^{-1}. A mechanical, balanced ventilation system with heat recovery unit efficiency of 70 % supplying air with a temperature of 19 $^{\circ}C$ at a rate of 10 m^3/m^2h during office hours and 3 m^3/m^2h during non-office hours is used for ventilation. The total window area is 20 % of the heated floor surface. The windows are distributed over the four walls as follows $A_{south} = A_{north} = 250\ m^2$, $A_{east} = A_{west} = 110\ m^2$. The glazed area constitutes 80 % of the total window area. The entire building has been simulated as a single heated zone.

4. Results

Simulations have been performed for the reference building and various control schemes of the solar shading system. When a shading system has been applied, the biggest possible ranges of variation of the solar heat gain coefficient (SHGC) have been assumed. This corresponds to zero solar heat gain in a closed position (set to 0.01 due to limitations in the simulation software). In the open position the same SHGC as for an un-shaded window has been used. For the two-pane window with U-value = 1.2 W/m^2K the SHGC is set to 0.55. For the three-pane window with U-value = 0.7 W/m^2K the SHGC is set to 0.45.

The calculation results are shown in Figures 3 and 4. The figures show the energy needed for cooling and heating the building, as well as the net energy demand. The net energy demand corresponds to the total energy use of the building, i.e including lighting, appliances etc. It is obvious from the figures that the heating demand is the larger than the cooling demand. The different series in Figure 3 and 4 shows the energy demands for different activation fluxes of the solar shading system. The activation flux is the incident solar radiation flux for which the shading system is activated. As long as the incident solar radiation is larger that the activation flux, the solar shading will remain in a closed position. Figure 3- and 4 indicates that the set-point for the activation flux can influence both heating and cooling demand. However, a reduction in cooling demand leads to a larger heating demand, thus evening out the effect on the net energy demand. The best thermal performance seems to be for the case with the lowest activation flux, although the difference in net energy demand is marginal. The only noteworthy way of reducing the net energy demand, is to use windows with a low U-value. However, the simulation tool used for the calculations does not make it possible to investigate the effect of altering the activation flux of the shading system dynamically over an annual cycle.

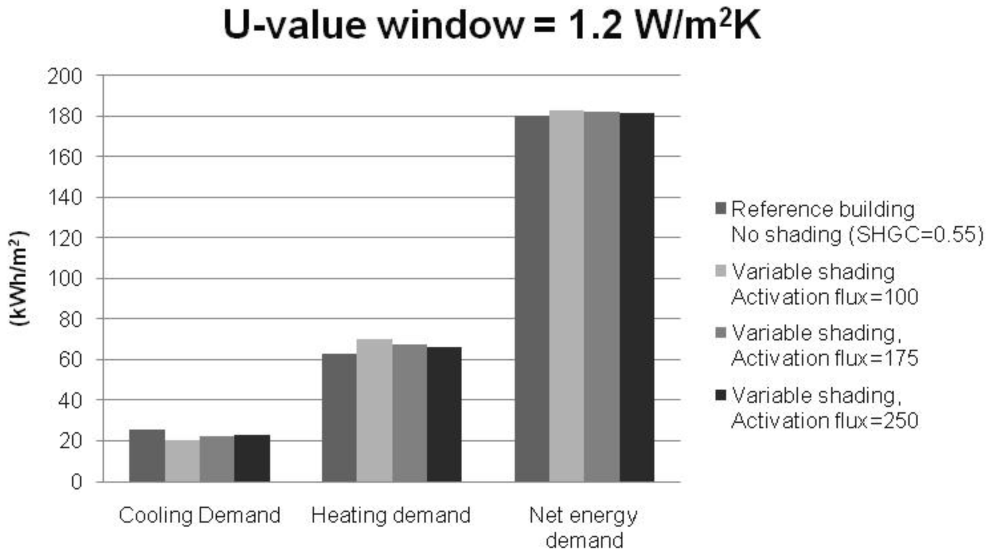

FIG 3. Calculated values for cooling-, heating and net energy demand for office building with two-pane windows. The net energy demand include energy use for lighting, appliances etc. in addition to the heating- and cooling loads. The shading systems have a SHGC values of 0.01 to 0.55 (that of the unshaded window) for the closed and open position respectively.

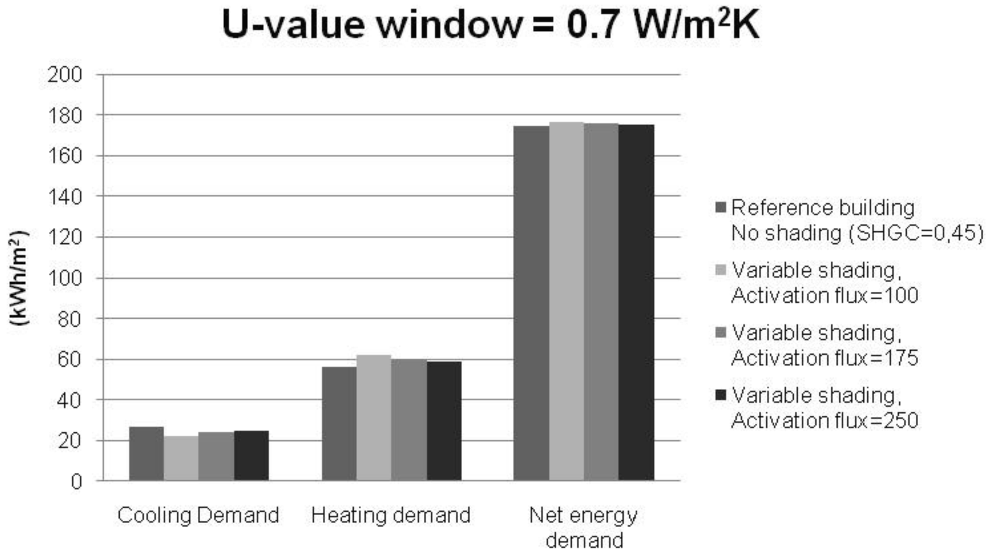

FIG 4. Calculated values for cooling-, heating and net energy demand for office building with three-pane windows. The net energy demand include energy use for lighting, appliances etc. in addition to the heating- and cooling loads The shading systems have a SHGC values of 0.01 to 0.45 (that of the unshaded window) for the closed and open position respectively.

5. Discussion

The effect of installing a solar shading system in the office building in question seems to have no or rather a negative effect on the net energy demand of the building. Figures 3 and 4 show that the single most effective measure to save energy is to replace the two-pane windows with three-pane windows. A reduction of window U-values will as expected reduce the total energy use of the building regardless of the effect of the solar shading system. In general one sees from Figures 3 and 4 that the cooling demand will increase with approximately 10 % as the window U-value decreases from 1.2 to 0.7 W/m^2K, but the heating demand will be lowered to a greater effect.

The range of the SHGC has been fixed for each of the two window types. In a practical window the upper limit of the SHGC might be slightly lower than for that of an un-shaded window, due to a slight blocking of incident solar radiation even in the open position.

As one can see from Figures 3 and 4 the control strategy seem to have a significant influence on the resulting cooling-, heating and net energy demand. If the operation of the shading system is regulated using erroneous governing procedures the result might be an increase in total energy demand due to a higher total energy use in spite of a reduction in cooling need. As a result one should further investigate which parameters that should control the opening and closing of the shading system. This study shows that using only the incoming solar radiation flux as a parameter for control can have negative effects on the total energy consumption.

5.1 Other aspects influencing cooling, heating and net energy use

It is vital that one does not optimize the performance of single components or systems in the building without looking at the building as a whole system that interacts closely. The simulations presented in this article do not take into account the effect on artificial lighting needs, and variations in internal gains.

In addition to the factors discussed in this article, one must however study the effects solar shading has on the energy use related to lighting, The need for artificial lighting will of course increase in pace with a reduction in natural lighting accessibility.

In the buildings of tomorrow it is probable that we will see a reduction of energy use for lighting (i.e. with the introduction of LED lighting). In addition energy use for TV-screens computers and such appliances could also be reduced in the future, thus reducing the internal gains in the building. These factors will also influence the effect and operation of any installed solar shading.

6. Conclusions and Future work

This work presents the main shading options for facades, and their effect on the SHGC and U-value.

Little work has been performed on state-of-the-art window and glazing technologies (i.e. high-performance windows with typical U-values in the range of 0.5 to 0.9 W/m^2K), and the effect that solar shading system have on the thermal performance of such windows. As the U-value of windows decreases, the effect of associated shading devices will be influenced. This is the case for both thermal and visible light performance. Further numerical and experimental studies should be performed to get a better understanding of these relations.

A summary of energy saving potential of similar shading systems as function of position i.e. internal, in-between panes or external should be presented. Typical state-of-the-art systems should be studied.

There has been found no information about numerical calculations where diurnal or annual climate-variations have been accounted for in terms of dynamically altering the properties of the solar shading systems in accordance with different needs over the year. Calculations exploring these possibilities should also be carried out.

7. Acknowledgements

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Scientific paper II

Steinar Grynning, Arild Gustavsen, Berit Time and Bjørn Petter Jelle

Windows in the buildings of tomorrow; Energy losers or energy gainers?

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Windows in the buildings of tomorrow: Energy losers or energy gainers?

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ABSTRACT

One of the most effective actions for reduction of energy loss through the building envelope is to optimize the thermal performance, area and localization of the transparent components in the façade in order to obtain minimal heat losses and optimal solar gains.

When considering the thermal performance of these transparent components, one should consider, not only heat loss (or gains) caused by thermal transmission, but also the beneficial effects of incident solar radiation and hence reduced demand for heating and artificial lighting.

This study presents calculations for a range of windows as part of a building where the coupled effects of incident solar radiation and thermal transmission heat losses are accounted for in terms of a net energy balance for the various solutions. Effects of varying thermal transmittance values (*U*-values) are studied in connection with solar heat gain coefficients.

Three different rating methods have been proposed and applied to assess the energy performance of several window configurations. It has been found that various rating methods give different energy saving potentials in terms of absolute figures. Furthermore, it has been found that windows, even with existing technology, might outperform an opaque wall in terms of heating and cooling demands.

1. Introduction

Energy demand in the building stock in Norway represents about 40% of the final energy consumption [1]. A substantial part of the energy use in the construction sector is directly related to the construction, operation and decommissioning of the actual buildings. The energy consumption is to a large extent related to the heating and cooling demands as well as lighting demands.

Previous studies show that a large part of the heat loss in buildings occurs through the glazed parts of the envelope. Grynning et al. [2] found that the heat loss related to windows contributes over 40% of the total heat loss through the building envelope for a typical Norwegian office building constructed according to the present Norwegian building regulations, known as TEK 10 [3]. The total heat loss distribution, excluding the ventilation heat loss, is shown in Fig. 1.

Based on the recommendations given in IEA ECBCS Annex 44 and the "Kyoto Pyramid" [4] combined with the fact that windows contribute to a substantial part of the heat losses one should further investigate the possibilities of reducing the heat loss related to all glazed and translucent parts of the facades. In addition, the glazed areas can give a positive contribution to the energy balance of the buildings by letting solar energy through, into the buildings and reduce heating demands during some periods. However, the use of glazed parts and components in a facade can also give raise to a cooling demand in the building.

In this article the combined effects of heat loss and heat gains are analyzed for a typical Norwegian office building. A parametric study have been performed using the building energy simulations (BES) modeling tool EnergyPlus [5] where the thermal transmittance (*U*-value) and solar heat gain coefficient (SHGC), also known as solar factor (SF), have been varied arbitrarily to investigate the effects they have on the energy balance of the windows using three distinct rating methods. One of the three methods, being the resulting heating and cooling demand for the building as function of *U*-value and SHGC combinations are also presented.

2. Window heat transfer

2.1. Window heat transfer mechanisms

The total heat flows through a window consist of conduction, radiation and convection driven by a temperature difference. Heat transported by conduction, long-wave radiation and convection is in general related to the total *U*-value of the window. Solar

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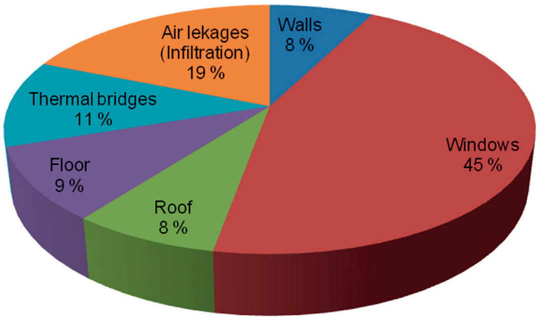

Fig. 1. Percentual distribution of heat losses through the various building envelope parts of an office building built according to the present Norwegian building regulations [2].

short-wave radiation will also be a large contributor to the heat flows, and is related to the SHGC of the window. The general energy transfer equation for a window is given in Eq. (1). The transmission heat flows, short-wave radiation contribution and the effect it has on artificial lighting demands are accounted for.

$$q_{\text{window,tot}} = q_{\text{transmission}} - \eta_{\text{shading}} \cdot q_{\text{sol}} - \Delta\xi_{\text{daylighting}} \quad (1)$$

where $q_{\text{window,tot}}$ is the total window energy balance (W/m^2), $q_{\text{transmission}}$ the Window transmission heat flow (W/m^2), η_{shading} the efficiency of shading system, q_{sol} the solar radiation level (W/m^2), $\Delta\xi_{\text{daylighting}}$ is the decrease of artificial lighting demand due to daylight (W/m^2).

2.2. *Window energy performance – state-of-the-art*

Numerous methods for rating window energy performance have been proposed in the existing literature. They range from very simplified methods where only the heating dominated period of the year is investigated to whole building specific numerical models of energy performance. The most relevant studies and methods are summarized below.

Investigations and calculations of window energy performance have been performed in several studies (see Table 1). Residential buildings are the type of building that has been studied most often. Only a few of the studies discuss the energy performance of windows in office buildings. The effect of window distribution on the heating and cooling demand of the building has been investigated. However, the buildings studied, are relatively poorly insulated with high *U*-values and thus do not give a representative picture for a building constructed with a low-energy envelope (e.g. passive house levels). The window properties are also somewhat outdated with higher *U*-values and lower corresponding SHGCs than what is achievable and more common with today's state-of-the-art windows.

For office buildings it is especially interesting to investigate the presumed effect of windows on the cooling demand in more detail. This does, however, make the performance related to internal gains, geometry and any other terms in the heat-balance of the building more complicated. Furthermore, it can be made a clear distinction between residential and public buildings. Residential buildings differ from commercial buildings in several aspects. Here, two are mentioned. Firstly, residential buildings have lower internal gains. Secondly, in general, no cooling plant will be installed in residential buildings.

The fact that cooling demands can be neglected in a residential building reduces the complexity of a simplified model and makes the construction of such a model less cumbersome than a model for an office building where cooling demands usually constitutes a large part of the energy demand, as is the case even in a Nordic climate.

2.3. *Performance rating methods*

2.3.1. *A Danish method*

A net energy gain value for residential buildings, has been proposed in Denmark [14]. Here, they present a method to account for both heat losses and heat gains through a window based on the *U*-value and the *g*-value (the same as the SHGC). Where the net energy gain is defined as:

$$E = g \cdot I - U \cdot D \quad (2)$$

where E is the net energy gain (W/m^2), g the solar energy transmittance, I the solar radiation (W/m^2), U the thermal transmittance (U-value) (W/(m^2 K)), D is the degree-day-number (K).

The method proposed by the authors [14] is a simplified model, which is valid for the heating season only. Thus making it less suitable for buildings where a cooling demand is prominent during warmer periods of the year. In these periods solar gains might give a negative contribution to the energy balance of the building by increasing cooling demands.

2.3.2. *A Spanish method*

Spanish researchers [15] have presented a window energy rating system (WERS), where they studied the useful energy for heating of the building as function of climate and building type. Here, they present two distinct methods. The annual useful solar heat gains are used as the base for the window energy rating. The authors [16] define a characteristic parameter, the balance temperature, T_b, which is a function of solar radiation levels ($Q_{\text{sol,u}}$), internal gains (Q_{int}), the total heat losses (K_{tot}) and the time interval considered ($\Delta\tau$), as given by:

$$T_b = T_{\text{int}} - \frac{Q_{\text{sol,u}} + Q_{\text{int}}}{K_{\text{tot}} \cdot \Delta\tau} \quad (3)$$

where T_b is the balance temperature (°C), T_{int} the indoor temperature (°C), $Q_{\text{sol,u}}$ the useful solar gain for building heating-system (kWh), Q_{int} the heat gains from internal sources (kWh), K_{tot} the building heat loss coefficient (kW/K), $\Delta\tau$ is the time interval (h).

T_b is used to find the proportion between the useful and total solar heat gain. The equation is solved in an iterative process whilst simultaneously solving the equation for $Q_{\text{sol,u}}$, given by:

$$Q_{\text{sol,u}} = S_g(T_b) \cdot A_g \quad (4)$$

where $S_g(T_b)$ is the cumulative radiation up to temperature T_b (kWh/m^2), A_g is the glazing area (m^2).

Then the equation shown in Eq. (5) is applied to evaluate the energy gain through the windows for all time-steps, where the external temperature, T_{ext}, is lower than the balance temperature, T_b, given by:

$$E = \sum \frac{(A' \cdot g_o + B' \cdot \alpha_f \cdot U_f - D' \cdot U_T - C \cdot L_{75})}{\eta} \quad (5)$$

where E is the energy gain through windows (kWh/m^2), A' the geometric factor to adjust solar irradiance (kWh/m^2), g_o = g-value of glazing at normal incidence, B' the factor accounting for surface heat resistances (kWh/m^2), α_f the absorptivity of frame, U_f = thermal transmittance of frame (W/(m^2 K)), D' the factor accounting for indoor/outdoor temperature difference (kKh), U_T the thermal transmittance of the window (W/(m^2 K)), C is the factor transforming L_{75} to realistic pressure differences (kWh/m^3), L_{75} the window infiltration rate at 75 Pa pressure difference (m^3/(h m^2)), η the annual fuel utilization efficiency.

Table 1
Window energy performance studies. Investigated parameter details for SHGC, U_g (W/m^2 K) and $U_{envelope}$ (W/m^2 K).

Type of building	Investigated parameter details	Climate	Additional information	Reference
Residential	SHGC = 0.5 U_g = 2.9/1.7/1 $U_{envelope}$ = 0.43/0.18	Stockholm, Berlin and Madrid	Shading included	[6]
Low energy house	SHGC = ? U_g = 0.7 $U_{envelope}$ = 0.10	Gothenburg	Window size and distribution	[7]
Residential	SHGC = 0.4–0.6 U_g = 0.6–1.4 $U_{envelope}$ = 0.17–0.18	Paris, Milan, Nice and Rome	Glazing properties. Window size. Low and no internal gains	[8]
Residential	SHGC = 0.4–0.6 U_g = 0.6–1.4 $U_{envelope}$ = 0.17–0.18	Stockholm, San Francisco, Miami	*U*-value vs. low-e coatings	[9]
Residential	SHGC = 0.02–1 U_g = 0.11–5.68 $U_{envelope}$ = 0.15–0.5	Fresno, Washington, DC, Minneapolis, Charleston, Salt Lake City	2500 combinations presented as windows use energy or windows produce energy. Dynamic SHGC studied	[10]
Office building	SHGC = 0.2–0.7 U_g = 0.92–1.65 $U_{envelope}$ = 0.18–0.32	Gothenburg	Window distribution. Window size and *U*-/SHGC. Shading systems included	[11]
Residential	SHGC = 0.42–0.76 U_g = 1.1–2.5 $U_{envelope}$ = 0.08–0.47	Stockholm	Window size/distribution. Window properties	[12]
Office (single cell)	SHGC = 0.5–0.8 U_g = 0.94–2.61 $U_{envelope}$ = 0.18	Stockholm	Window size, direction, properties and daylighting	[12]
[1,0]Office (single cell)	SHGC = 0.16–0.86 U_g = 1.0–2.6 $U_{envelope}$ = 0.18	Lund, Stockholm, Luleå, Oslo, Montreal	Window size, direction, properties and daylighting Indoor climate, comfort	[13]

Hence, the fact that solar radiation might lead to a cooling demand when internal temperatures exceed that of the cooling set-point temperature is disregarded. Furthermore, they compare the proposed method with results using the building energy simulation (BES) tool TRNSYS [17]. They conclude that windows with a low emissivity coatings and high SHGC are desirable in a cold or temperate climate and that triple glazing units can give a greater energy savings in cold climates compared to temperate climates.

2.3.3. An Italian method

The authors [18] present three separate building cases which have been studied in order to introduce a rating scheme. Five different, Italian climates have been studied. The ratings proposed are functions of window properties, climate conditions and the architectural characteristics of the residential building. Both cooling and heating loads were considered with the use of detailed simulations using the BES tool TRNSYS [17]. The simulation results were used to define a simplified algorithm using different regression approaches which can be used to rate the window heating load reduction (HLR) and cooling load reduction (CLR) potentials.

A normalized HLR coefficient (NHLR) is defined which is based on the window transmission heat losses, infiltration heat loss caused by the windows in the building and the average winter solar radiation (R_{inv}) over the four cardinal directions. Similarly, a normalized CLR potential (NCLR) is proposed as function of *U*-value, *g*-value and air leakages.

The analysis has been performed on windows with *U*-values of 2.6 W/(m^2 K) and higher and it does not discuss how other building types and/or climate conditions would influence the rating factors found by the performed regression analysis. However, the authors point out that further investigations of the energy-rating schemes are required.

2.3.4. A Canadian method

Through the IEA SHC Task 27, a Canadian workgroup has proposed a simplified energy rating model for windows [19]. Here, they also present an overview of which parameters that must have a clear and specific measure in order to be able to characterize an energy efficiency level. The parameters are: *U*-value, SHGC, visible transmittance (T_{vis}) and condensation resistance. Based on these parameters a simplified equation is proposed (Eq. (6)), which is used to calculate the energy rating (ER).

$$ER = 0.8 \cdot 72.2 \cdot SHGC - 21.9 \cdot U_w - 0.54\frac{L_{75}}{A_w} \quad (6)$$

where ER is the energy rating (W), $SHGC_w$ the solar heat gain coefficient of a window, U_w the overall heat loss coefficient (W/m^2 K), 72.2 the factor to account for average solar radiation on a vertical window, during heating season (W/m^2), 0.8 the factor to account for exterior shadings on windows, 21.9 the average temperature difference over the heating season (°C), 0.54 the factor adjusting air leakages at 75 Pa pressure difference to real pressure average difference, L_{75} the air leakages related to the window at a 75 Pa pressure difference (Pa), A_w is the window area (m^2).

However, the rating method is valid only for the heating season, and the multiplication factors to account for average solar radiation, and temperature difference are calculated for Canadian climates only.

Furthermore, the author has performed simulations of energy consumption for a residential house as function of SHGC variations for the windows. The *U*-value was kept constant at 2.0 W/(m^2 K). It was found that a window with a SHGC in the range 0.3–0.4 gives the lowest energy demand. For a small commercial building it is concluded that a SHGC of 0.35 gives the cost-optimum solution.

2.3.5. Methods summary

Common for all the simplified methods proposed, is that all but the Italian method consider the energy balance during the heating season of the year only. This might be adequate for residential buildings, but not for buildings with cooling loads. Good performances during a period with a negligible cooling demand might not necessary indicate a good performance during the cooling dominated period of a year. It is a fact that office buildings with a large amount of transparent surfaces toward south will have a cooling demand during extensive periods of the year, even in a cold climate like, e.g. Norway [20].

Furthermore one can see a clear similarity between the Danish and the Canadian method. The energy rating for both methods revolves around accounting for solar gains as a positive contribution, and heat losses as a negative factor. The main difference is that the Canadian method accounts for air leakages related to the windows as a separate term.

The Danish, Spanish and Canadian methods, all describe simplified models with a somewhat generic usefulness, but they all have certain limitations in that they are applicable only to residential buildings where cooling loads are minor.

The Italian method describes the procedure for rating both the cooling and heating performance, but is limited in that it is based on regression analyses for only a limited number of climate conditions and windows with a high *U*-value of 2.6 W/(m^2 K).

3. Methods

3.1. Software, simulations and input values

Simulations for an entire year have been performed for a building using the BES software EnergyPlus [5]. A five minute time-step was used to perform the calculations. In the calculations, the effect of solar heat gains through windows and window heat loss on the heating and cooling demand of the office building has been considered. A study of *U*-value and SHGC variations has been performed. The *U*-values have been varied from 0.2 W/(m^2 K) to an upper limit of 1.2 W/(m^2 K). The upper level of 1.2 W/(m^2 K) is the upper limit for *U*-values that can be used in new buildings according to the Norwegian building regulations [3]. The SHGC has been varied in steps of 0.2 from a lower limit of 0.2 up to 0.8. The upper limit was set since reaching higher SHGC than 0.8 is not practically feasible due to reductions in transmittance by the glass itself.

Finally, a double-, triple-, and four-pane window have been constructed using WINDOW 6.0 [21]. The combinations of *U*-value and SHGC assessed using the three methods have been carried out with theoretical combinations of *U*-values and SHG coefficients. A combination of, e.g. low *U*-value and a high SHGC is not possible to obtain with existing materials and technology. Therefore, three state-of-the-art windows have been constructed and assessed applying the three methods. These windows represent the state-of-the-art for windows available on the market today. *U*-values and SHGC from the calculations have been used as input for rating the three windows using the three methods proposed in this work.

3.2. The office building in question

Simulations for an office building situated in Oslo (latitude, 59.91°N), Norway have been performed. The office building is a typical mid-size Norwegian building with a ground floor area of 1200 m^2 (30 m by 40 m, with the 40 m sides oriented north-south) and three stories, giving a total heated area, A_{BRA} = 3600 m^2. The window area was set to 690 m^2, equaling 20% of the A_{BRA} (this equals a window to wall ratio, WWR, of 55%). It is constructed so as to fulfill the Norwegian passive house standard for dwellings, NS 3700 [22]. This results in *U*-values for the roof, walls and floor of 0.13, 0.15 and 0.15 W/(m^2 K) respectively, and an airtightness of the envelope of 0.7 h^{-1} at 50 Pa pressure difference. Internal loads, ventilation schemes, operational hours, etc. have been set according to standard values for office buildings given in the Norwegian standard for energy performance calculations, NS 3031 [23]. A simplified three-zone model, as specified in NS 3031, for each of the floors has been used. This implies creating a 5 m deep sun-exposed zone to the south, a 20 m deep central zone and a third 5 m deep zone toward the north.

3.3. Model simplifications

The SHGC is in practice an angular dependent variable. Depending on glazing properties, the value of the SHGC will vary as function of solar height and azimuth. In this work the simplified model for windows implemented in Energy Plus has been used. The SHGC is given as a constant, non-angular dependent value as input to the simulation software.

Air leakages related to mounting of windows in walls might have a substantial effect on the total infiltration heat losses of a building. The mounting of windows are, however, not dependent on the glazing properties and is therefore not a variable when performing a parametric study on *U*-value and SHGC combinations. Based on this, all heat losses due to window air leakages have been disregarded in this work as they may be considered constant and thus have been included as a part of the total infiltration heat loss of the building.

The daylighting levels in a building will also influence the energy demand of the building. A high level of transmittance of visible light (T_{vis}) can lower the demand for artificial lighting. The effect different T_{vis} values of the glazing systems have on the demand for artificial lighting is not within the scope of this study. Nor have the effect of installing solar shading systems been studied in this work. This will be evaluated in later studies.

3.4. Window rating methods

The energy performance of the windows studied in this work has been rated by use of the three different approaches as listed below:

1. ISO 18292:2011; *Energy performance of fenestration systems for residential buildings – calculation procedure* [24].
2. The useful gain method (proposed below).
3. The effect on the combined cooling and heating demand of the building.

3.4.1. ISO 18292 method

The ISO 18292 [24] standard suggests a simplified method for assessing the energy performance of fenestration systems for residential buildings. For Norwegian residential buildings, local cooling in dwellings should be avoided in new buildings erected in accordance with the present Norwegian building regulations [3]. Application of the method to an office building has nevertheless been made. The method gives two separate rating factors; a cooling rating factor p_c and a heating rating factor p_h. The factors are an indication on how the window system affects the energy demand of the building and are given on the form kWh/(m^2 window area and year). That is, a negative factor indicates a reduction of cooling or heating demand and is thus beneficial in terms of energy savings. An adiabatic element, with zero heat loss and zero heat gain, replacing the window is the reference element used in this method.

For ease of comparison to the other two methods proposed, the figures in this article have been converted into a rating factor

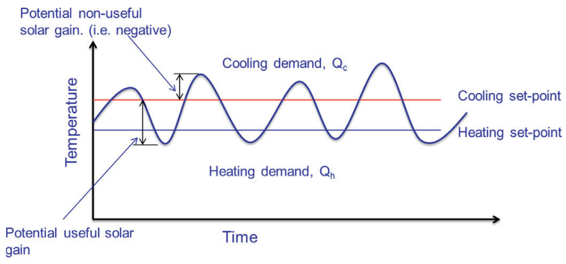

Fig. 2. Schematic illustration of potential usefulness of solar gains as function of internal temperature and cooling and heating set-point temperatures.

per m^2 floor area, A_{BRA}, thus giving figures in the following format $kWh/(m^2\ A_{BRA}\ year)$.

3.4.2. Useful gains method

The second method proposes a performance rating method where a defined useful gains factor is studied. Combined with the heat losses of the window this gives an assessment of the usability of any solar heat gains that enter via the windows and the useful energy balance of the windows.

Heat losses through windows contribute to an increased energy demand, when the building is in demand for heating. On the other hand, solar gains might contribute to reduce the energy demand for heating the building. The solar heat gains might lead to an increased cooling demand, thus contributing to an additional energy demand of the building. Fig. 2 shows a schematic illustration of this.

Fig. 2 shows an arbitrary temperature cycle as function of time. If the temperature exceeds the cooling set-point temperature, a cooling demand is induced. If at the same time, there are solar gains present, these will be considered non-useful (i.e. negative) as they contribute to the cooling demand. Depending on the ratio of the cooling demand to the solar gain level, two zones may be defined, as discussed in the following.

If the temperature drops below the cooling set-point temperature, all solar gains are considered useful (i.e. positive). This correlates to the third zone for the usefulness of the gains as discussed in the following. Considering all of these gains as useful is arguable. Some of the gains will directly contribute to heating the building and help to rise the temperature toward, up to or past the heating set-point temperature, whereas some gains will only shift temperatures within the comfort zone (i.e. between heating and cooling set-point temperatures). An additional effect not accounted for in the proposed method is that temperature shifts due to solar heat gains could influence the cooling demands when the set-back for heating and cooling are shifted at the end and start of operational hours.

Based on the previous discussion, three characteristic zones for the *usefulness* of the solar heat gains are defined:

1. Cooling demand > solar gains (e.g. cooling demand of 200 W and a solar gain of 100 W)
2. Cooling demand < solar gains (e.g. cooling demand of 100 W and a solar gain of 200 W)
3. No cooling demand

Based on these three zones one can define a useful gain factor at a time-step i, $q_{ug,i}$, as shown in Eq. (7), for each zone.

1. All solar gains are considered negative $\Rightarrow q_{ug} = -$solar gains
2. The cooling demand part of the solar gains is considered negative $q_{ug} = -$cooling demand
3. All solar gains are considered positive $\Rightarrow q_{ug} =$ solar gains

The useful gain can then be combined with the heat loss through the window to give the useful energy balance of the window, $Q_{window,useful}$, as shown in Eq. (7). It is noted that this evaluation has to be performed for each time step of the simulations performed and for each of the zones of the building.

$$Q_{window,useful} = \sum((q_{ug,i} - q_{loss,i}) \cdot \Delta T) \qquad (7)$$

where $Q_{window,useful}$ is the useful energy balance for windows $(kWh/(m^2\ A_{BRA}\ year))$, $q_{ug,i}$ the useful solar gain through window at time-step i $(J/(m^2\ A_{BRA}))$, q_{loss} the heat loss through window at time-step i $(J/(m^2\ A_{BRA}))$, Δt is the simulation time-step length (s).

To ensure coherence with the ISO 18292 method and ease of comparison of results the useful gain is defined as being beneficial in terms of reduction of energy demand. Thus negative values for the useful gains and useful energy balance will give a reduction of heating and cooling demands. As for the ISO 18292 method, simulated values are given per m^2 heated floor area $(kWh//(m^2\ A_{BRA}$ and year)). One can easily convert the numbers to a per-window area basis by multiplying with the heated floor area (m^2) and dividing on the window area (m^2).

3.4.3. Cooling and heating demand method

The third approach for assessing the energy performance of the windows was performed by studying the heating and cooling demand of the building as function of *U*-value and SHGC variations. A case, where all windows are replaced with an opaque wall (with the same *U*-value as the rest of the building) was used as a reference comparison case. As for the other two methods, simulated heating, cooling and combined heating and cooling are stated on a per square meter heated floor area.

4. Results and discussion

4.1. ISO 18292 method

The application of the ISO 18292 method shows that the windows give a beneficial contribution to the heating demand of the building for most combinations of *U*-value and SHGC. The *y*-axis of the graphs shown in Figs. 3–5 gives values for how the windows influence the heating, cooling or combined heating and cooling demand. Thus, negative values indicate that the window reduces the net demand.

From Fig. 3, we see that a window with a SHGC of 0.6 gives the lowest (most beneficial) possible heating performance contribution for the windows with *U*-values of 0.6 $W/(m^2\ K)$ and lower. Increasing the SHGC further gives a decrease to the heating performance.

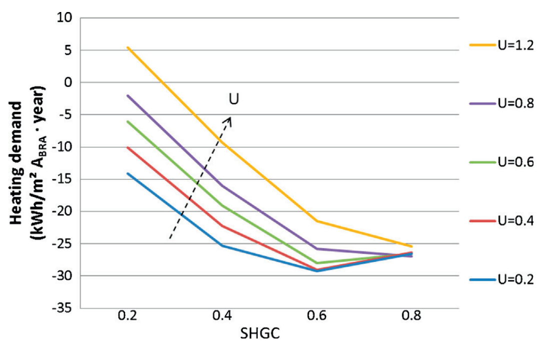

Fig. 3. Heating demand (performance) of windows $(kWh/(m^2\ A_{BRA}\ year))$ for Oslo climate. Values calculated according to procedure given in ISO 18292 [24].

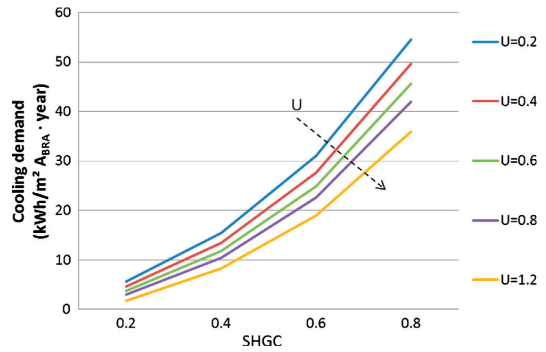

Fig. 4. Cooling demand (performance) of windows (kWh/(m^2 A_{BRA} year)) for Oslo climate. Values calculated according to procedure given in ISO 18292 [24].

From Fig. 4, one can see that an increase of the SHGC gives a significant increase in the cooling demand for the building.

If one look at the combined effect on both cooling and heating demand of the building, we see from Fig. 5, that an optimum window configuration with a SHGC = 0.4 and a *U*-value = 0.2 W/(m^2 K) gives the lowest possible performance rating factor. Windows with a *U*-value of 1.2 W/(m^2 K) combined with SHGC between approximately 0.38 and 0.64 results in configurations that can reduce the energy demand of the building. This method also shows that *U*-values lower than 0.8 W/(m^2 K) combined with a SHGC between 0.2 and 0.6 gives a negative (i.e. beneficial) performance rating.

4.2. Useful gains method

The second method shows the energy balance of the windows, as discussed in the methodology chapter. It is noted that to make figures coherent with the ISO 18292 method, the term useful gains are used with reference to reduction of energy demand. Popularly speaking, this means that a negative useful gain means one can subtract that figure from the energy bill, thus making it useful.

The amount of useful gains depicted in Fig. 6 shows that large solar gains in general must be associated with a cooling demand, thus increasing the energy demand of the building. Furthermore, one can see that a SHGC of 0.4 gives the optimal window configuration regardless of *U*-value when considering the useful gains (for this particular building and climate). If the SHGC is higher than 0.4, cooling demands reduce the amount of useful gains. SHGC

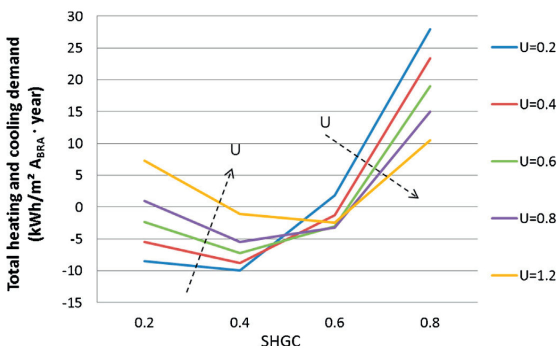

Fig. 5. Combined heating and cooling demand (performance) of windows (kWh/(m^2 A_{BRA} year)) for Oslo climate. Values calculated according to procedure given in ISO 18292 [24].

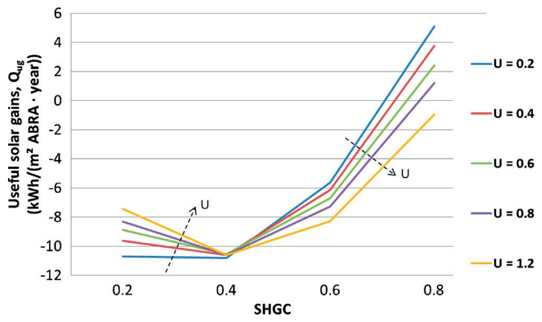

Fig. 6. Useful solar gains ($Q_{ug} = \sum(q_{ug,i})$) from the window distributed on the heated floor area (kWh/(m^2 A_{BRA} year)) for Oslo climate.

lower than 0.4 gives higher heating demands and thus reduces the amount of useful gains.

Fig. 7 shows the defined useful energy balance of the windows according to the useful gains method. Several *U*-value and SHGC combinations will in theory give windows that reduce the energy demand of the building. In the same figure, the energy balance of an opaque wall is shown. The opaque wall will always be associated with a heat loss, since no solar gains are practically achievable. A window with *U*-value 0.6 W/m^2 K and SHGC of 0.6 has the same useful energy balance as an opaque wall. For even lower *U*-values it is possible to have windows that give a positive contribution to the energy balance of the building. This makes it a *net energy gainer* according to the proposed method. Following the same trend as the useful gains showed in Fig. 6, the useful energy balance reaches an optimum for a SHGC of 0.4.

4.3. Heating and cooling demand rating

In the following, we see how the heating and cooling demand of a building varies with the *U*-value and SHGC-values for the windows. In Figs. 8–10, the energy demand for heating, cooling and the combined heating and cooling divided on the heated floor area of the building are shown.

From Fig. 8, we see a drop in heating demand, as function of a reduced *U*-value and an increasing SHGC value. Focusing solely on the heating demand suggests that low *U*-values combined with high SHGC values should be aimed at. Furthermore, it is shown that the heating demand can be reduced by more than 50% for the windows with the lowest *U*-values compared to the reference case where the windows have been replaced with an opaque wall with the same *U*-value (0.15 W/m^2 K) as the rest of the walls.

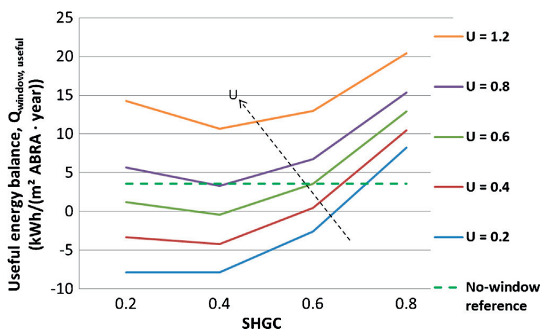

Fig. 7. Useful yearly energy balance of the window ($Q_{window,useful}$) distributed on the heated floor area (kWh/(m^2 A_{BRA} year)) as calculated from Eq. (4) for Oslo climate.

Table 2
Comparison of energy savings potential for three windows using the proposed methods.

	Energy demand saving potential (kWh/(m^2 A_{BRA} year))		
	ISO 18292	Useful gains method	Heating and cooling demand[a]
2-Pane window*U*-value/SHGC = 1.2/0.50	−2	12	45(10)
3-Pane window*U*-value/SHGC = 0.8/0.34	−4	4	35(3)
4-Pane window*U*-value/SHGC = 0.4/0.28	−7	−4	32(−3)

[a] Figures in brackets show the heating and cooling demand for the window configuration compared to (subtracted from) the heating and cooling demand of the opaque wall reference case. Hence, the four-pane window will act as a *net energy gainer* compared to an opaque wall.

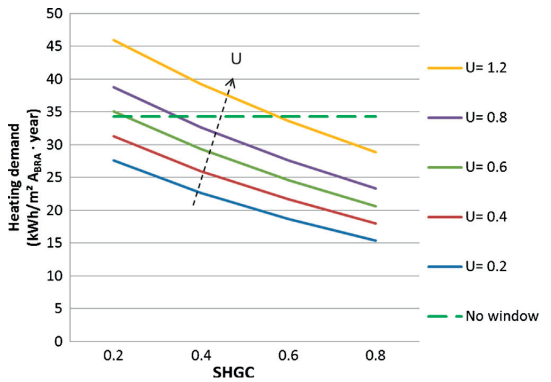

Fig. 8. Heating demand for office building (kWh/(m^2 A_{BRA} year)) for Oslo climate. Values from EnergyPlus simulations.

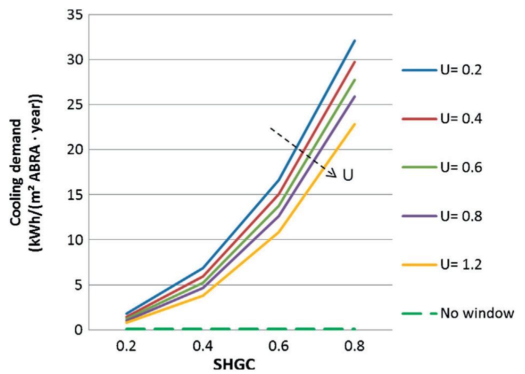

Fig. 9. Cooling demand for office building (kWh/(m^2 A_{BRA} year)) for Oslo climate. Values from EnergyPlus simulations.

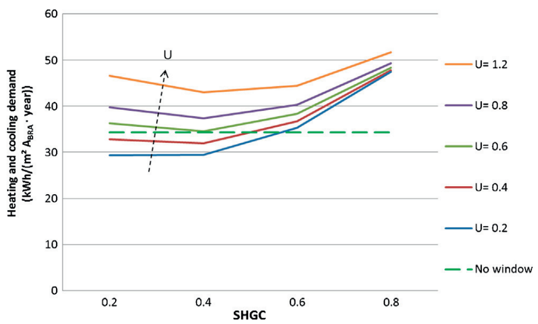

Fig. 10. Combined sum of heating and cooling demand for office building (kWh/(m^2 A_{BRA} year)) for Oslo climate. Values from EnergyPlus simulations.

In contradiction to the heating demand, the introduction of a cooling demand, as shown in Fig. 9, suggest that one should decrease the SHGC values as much as possible to reduce cooling demands. The largest energy savings potentials are for high SHGC values. The gradients of the curves lessen when the SHGC are approaching 0.2.

When summing up both heating and cooling demands, we see similarities in the performance to both the ISO 18292 method and the useful gains method. As shown in Fig. 10, the combination of a lowest possible *U*-value and a SHGC value of 0.4 give the lowest combined heating and cooling demand. Fig. 10 shows that windows with a *U*-value lower than 0.4 W/(m^2 K) and SHGC below approximately 0.5 will give a net heating and cooling demand lower than for the reference case where windows are replaced with an opaque wall.

4.4. Comparison of results from different methods

The three methods show somewhat incoherent results regarding the energy performance of the building and the studied window configurations. In general, the ISO 18292 method gives the highest energy savings potential for the windows. A combination of SHGC < 0.6 combined with any *U*-value gives a combined heating and cooling demand below zero, i.e. defining them as gainers.

Fig. 10, representing a combined sum of heating and cooling demand, shows that it is possible to reach a lower energy demand by use of windows rather than an opaque wall. The method does not, however, show the energy balance of the windows.

The second method utilizing the useful gains definition gives more conservative results than the ISO 18292 method. Windows with *U*-values below 0.4 combined with SHGC below 0.6 can, according to the results in Fig. 7, be classified as energy gainers.

All the three methods show that an optimal SHGC of the windows can be found. For the studied building, the most beneficial combination of *U*-value and SHGC is found with SHGC of 0.4.

Table 2 shows a comparison of the energy savings potential ratings using the three methods for three state-of-the-art windows.

Table 2 demonstrates that the three methods give different energy demand saving potential for all three windows. The difference is largest for the double-pane window, but the discrepancy is still high for the four-pane window. Nevertheless, regardless of method, it was found that a four-pane window will give a beneficial impact on the energy demand compared to an opaque wall.

5. Conclusions

The energy balance of a window and the effect of window properties on the energy demand of a building is a complex interaction of a large array of parameters. Previous studies show only the heat loss factors for building components and performance during the heating season of a year. This gives a biased impression of the window energy performance as it does not take into account any cooling demands of the building as a result of the window properties.

The results from the simulations carried out in this work show that cooling demands are dominating in office buildings even in what is commonly considered to be a heating-dominated cold climate like Oslo in Norway.

Three methods have been proposed and used to assess the energy performance of windows in an office building. The three methods give different energy savings potential in terms of absolute figures. The ISO 18292 method gives an optimum solar heat gain coefficient (SHGC) of 0.4 for windows with *U*-values lower than 0.8 W/(m^2 K). The other two methods suggest that low *U*-values combined with SHGC around 0.4 are desirable also in a cold climate due to substantial cooling demands.

Typical state-of-the-art windows available on the market today, can reach *U*-values as low as 0.4 W/(m^2 K) whilst still maintaining a SHGC of approximately 0.3, using a four-pane glazing unit. This makes them equal to or even better performing than highly insulated opaque walls with respect to the total heating and cooling demand. These windows may then be classified as *net energy gainers*.

Furthermore, it was found that a reduction of the window *U*-value from 1.2 to 0.8 W/(m^2 K) (i.e. going from a double to a triple pane insulated glazing unit) can reduce the energy demand for heating and cooling with 5–15% depending on the SHGC. Other building configurations may lead to in different results.

The introduction of dynamic solar shading systems is vital to lower the energy demands further than what is possible with unshaded windows.

6. Further work

The simulations performed in this work should be considered as the first phase of a work assessing energy performance of windows in office buildings. The useful energy balance of the windows may be used as input also for life cycle assessment (LCA) investigations. Further studies will include implementing dynamic solar shading systems and the effect of solar radiation on the artificial lighting demand. Control strategies and state-of-the-art systems should be investigated. Glare effects and comfort should also be included to give a better understanding of how shading systems affect, not only thermal performance, but also both the thermal and visual comfort in office buildings. New technologies for lighting (LED lighting) and technical equipment producing less heat are developing rapidly. This influences internal gains for office buildings even more. The effects of a reduction of cooling and heating demand should also be investigated.

Acknowledgments

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Scientific paper III

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Solar shading control strategies in cold climates – Heating, cooling demand and daylight availability in office spaces

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Solar shading control strategies in cold climates – Heating, cooling demand and daylight availability in office spaces

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Abstract

Modern office buildings often have large glazed areas. Incident solar radiation can lead to large cooling demands during hot periods although the solar radiation can help reduce heating demands during cool periods.

Previous studies have shown that large parts of the net energy demand of an office building is related to window heat loss and cooling demands induced by solar irradiance. In this article, the authors found that, even in what traditionally has been considered to be a heating-dominated climate, cooling demands dominate the net energy demand of an office building. Solar shading systems are vital to reduce the cooling demand of an office building.

Introducing shading systems might contribute to higher heating demands as well as higher demands for artificial lighting but at the same time it might be necessary in order to reduce glare issues.

Simulations of a number of shading strategies have been performed for south- and north-facing office cubicles with varying floor areas, window sizes and window parameters. Energy demands for heating, cooling, lighting and ventilation fans have been assessed. The simulations show that the choice of shading strategy can have an impact on the energy demand of the offices. Depending on strategy, the energy demand can either increase or decrease compared to an unshaded one- or two-person office cubicle.

In addition, the shading systems can contribute toward a lowered thermal transmittance value (*U*-value) of the window by functioning as an additional layer in the glazing unit when closed. Potential improvements of *U*-values have been studied in combination with the shading system's effect on solar heat gains and daylight levels. Experimental investigations of in-between the panes solar shading system effects on window *U*-values are currently being carried out at the Research Centre on Zero Emission Buildings (www.ZEB.no).

It was found that automatically controlled shading systems can reduce the energy demands of south-facing, small office cubicles, but that they should not be installed without a thorough case-by-case investigation as increased energy demands were found if an improper shading strategy was chosen. Upgrading to four-pane glazing will, however, always have a beneficial impact on the energy demand compared to two- and three-pane glazing.

Keywords: Solar shading; Heating demand; Cooling load; Daylight

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1. Introduction

1.1. The task at hand

Modern office buildings often have large glazed areas toward the exterior where the glazed parts of the building envelope can constitute a substantial part of the total area. This makes them especially exposed to and dependent on solar radiation, which can lead to large cooling demands during hot periods. However, the solar radiation can help reduce heating demands during hot periods. Thus, solar shading devices become important for optimizing and controlling solar radiation entering the offices.

Existing studies Dubois and Blomsterberg (2011) and Silva et al. (2012) have found that control strategies are not without flaws, making for higher real energy consumption than simulations have predicted. The sensitivity analysis performed in this work sheds light on how to better accommodate user behaviour in the design of shading control strategies and how to make the control strategies more robust, focusing on a cold climate.

Previous studies also show that large parts of the net energy demand of an office building is related to window heat loss and cooling demands induced by solar irradiance. In this study (Grynning et al., 2011), the authors found that even in what traditionally has been considered to be a heating-dominated climate, cooling demands dominate the net energy demand of an office building. Solar shading measures are vital for reducing the cooling demand of an office building.

Simulations of a number of shading strategies have been performed for south- and north-facing office cubicles with varying floor areas, window sizes and window parameters. The aim has been to optimize shading strategies and window properties in order to reduce energy demands for heating, cooling and artificial lighting while maintaining adequate thermal and visual comfort levels for the users. An additional intention of the study has been to investigate the reliability of commercially available software developed for the purpose of studying the performance of glazed façades.

1.2. Energy performance of shading systems – existing studies

As several previous studies have found, automatic control of shading is essential for realizing the energy-saving potential and daylight benefits of the shading systems. The control methods must simultaneously include both lighting and cooling energy demands (Kim et al., 2007). This should ideally be extended to also include heating energy. Control strategies must, in addition, be tailored to perform in its designated climate. The best strategy will vary greatly depending on the type of climate. Manual control should be avoided from an energy-saving point of view because users of the buildings tend to leave the blinds either open or closed regardless of what is optimal with respect to cooling/heating need and or daylight levels (Reinhart and Voss, 2003; Nielsen et al., 2011). However, it should be noted that user preferences often contradict such automatic systems. Studies regarding user behaviour and occupant preferences (Stevens, 2001; Galasiu and Veitch, 2006; Thunshelle and Hauge, 2012) have found that occupants tend to prefer manual control and the possibility to override automatic systems. Regardless of this, it is important to investigate and optimize automatic controls, which is why the authors chose to focus on the automatic control systems in this work.

Furthermore, the choice of strategy is important in order to optimize the use of solar gains. Several studies have been performed where control strategies and patterns of various shading systems have been studied (Tzempelikos and Athienitis, 2007; Koo et al., 2010; Appelfeld et al., 2012; Goia et al., 2013). In van Moeseke et al. (2007) it was found that in order to reduce heating demands during winter, a combination of solar irradiance levels and internal temperature set points should be used. This will ensure better utilization of solar gains for heating during wintertime.

1.3. Overview of key performance and assessment parameters

Several aspects must be considered in order to fully understand the performance of the glazed parts of a façade. In addition to the energy use for heating, cooling and lighting, visual comfort must also be satisfactory in order to classify a system as performing well.

1.3.1. Daylight and solar heat gains – effect on cooling and heating demand

Overheating is a major concern for modern office buildings, even in cold climates. Thus, solar shading systems must be introduced in these buildings in order to reduce the energy demand for cooling. A properly designed shading system must, however, handle several important issues.

1.3.2. Daylight, visual transmission – illuminance levels and artificial light

In order to maximize the use of daylight, a high visible transmittance factor (T_{vis}) is desirable.

Previous studies state that large energy savings can be found through optimization of the artificial lighting design A lowered lighting power density (LPD) has two major benefits: reducing the energy demand for lighting and reducing the internal loads, thus contributing to lowering the office's cooling demands.

Detailed studies of offices show that energy consumption for lighting can be more than halved by using modern, controlled systems. This corresponds to the findings by Bülow-Hübe (2001), where the author found that electricity demand for an office building in Gothenburg could be reduced from 23 kW h/m^2 year to 11 kW h/m^2 year. LPD levels of modern offices should, according to the European standard NS-EN 15193 *Energy performance of buildings – Energy requirements for lighting* (NS-EN, 2008), be aimed at reaching 8 W/m^2 for normal offices. The Norwegian standard for energy calculations, NS 3031 *Calculation of energy performance of buildings – Method and data* (NS, 2011), takes it one step further by stating that a yearly average LPD of 5 W/m^2 is sufficient to ensure adequate lighting levels in low-energy and passive house standard offices; however, the reason for this low level is not clarified in the standard. In this work, a choice has been made to keep the NS-EN 15193 LPD level of 8 W/m^2 for the simulations performed. The choice was based on the unfounded description of LPD levels in the NS 3031 standard and the fact that NS-EN 15193 is an international standard and is therefore likely to give a more general representation of LPD levels.

1.3.3. Thermal transmittance of glazing units with in-between shading

An in-between pane type of shading system will influence the thermal transmittance value of the glazing system. When the shading slats are closed, it can function as an additional layer in the glazing unit. On the one hand, this might reduce the *U*-value of the glazing system; on the other hand, an increase in the *U*-value is anticipated when the slats are in the open position, making them into thermal bridges between the hot and cold side of the cavity (Tzempelikos, 2005). The additional hardware that needs to be mounted in the glazing cavity will also contribute to a higher *U*-value of the glazing unit. Experimental investigations are currently being performed as part of the work carried out by the Research Centre on Zero Emission Buildings (www.ZEB.no).

1.3.4. Daylight – glare indexes and visual comfort

The glare index (GI) is, in this context, used to estimate the amount of discomfort glare caused by the windows in an office space. The GI factor is basically a quantified index that describes the difference between the luminance of an object in relation to the luminance of interior surfaces surrounding the window, as seen from a reference point (Hopkinson, 1972). Several correlation formulae have been proposed throughout the last 40–50 years (Osterhaus, 2005).

The discomfort glare index (DGI) is related to set levels of the GI where human perception of the glare takes on different forms. The degree of discomfort is measured in terms of reduced performance of a given task. The DGI limits for office work as defined in the EnergyPlus software manual (EnergyPlus, 2012) are shown below.

- 16: Just perceptible.
- 20: Just acceptable.
- 22: Borderline between comfort and discomfort.
- 24: Just uncomfortable.
- 28: Just intolerable.

This corresponds to NS-EN ISO 12464-1:2011 – *Light and lighting – Lighting of work places – Part 1: Indoor work places* (NS-EN, 2011), where the boundary for acceptable GI is set at 22. However, it is important to be aware that there are uncertainties regarding how glare is perceived. This could be caused both by calculation procedures of the DGI as well as differences in human perception of glare (Bellia et al., 2008).

Based on these limiting values for the DGI, adjustments can be made to a solar shading system control strategy in order to stay below certain glare levels. However, it should be noted that an in-between glazing shading system might not be the most efficient system for handling glare. Internal shades or curtains manually operated by the user could be considered as a low-tech but efficient solution for reducing unwanted glare, especially during winter when solar radiation can provide useful gains in terms of reducing the heating demand.

Daylight illumination levels are also important in helping to reduce the need for artificial light. Daylight is thought to have beneficial impacts on humans, including improving work efficiency. Nabil and Mardaljevic (2006) found, after an extensive literature review, that daylight illuminance levels are beneficial when in the range of 100–2000 lux. The maintained illuminance level for a workspace should, according to standard NS-EN 12464–1:2011 (NS-EN, 2011), be higher than 500 lux. Reinhart and Weissman (2012) carried out a study where 60 architectural students made subjective assessments of the daylight quality in a room. Their assessments were compared to some of the most common daylight metric methods and levels found in the literature. They found that a target illuminance level of 300 lux or more coincided with what the students considered to be a well daylit room. The traditional daylight factor did not align so well with the assessment of the daylit space.

A description of the assessment methods used in this work is presented in Section 2.2.1.

1.3.5. Thermal comfort – Fanger's model

Thermal comfort is assessed using the Fanger comfort model (Fanger, 1967). Fanger's model is based on an energy analysis that accounts for all the modes of energy loss from the body. The model encompasses air and mean radiant temperature along with the applicable metabolic rate, clothing insulation, air speed and humidity to predict thermal comfort. The heat balance is combined with experimentally derived physiological parameters in order to predict the thermal sensation and the physiological response of a person due to their environment. This is quantified here as the Predicted Percentage of Dissatisfied people (PPD). A thorough description of the model can be found in the simulation tool description (EnergyPlus, 2012).

2. Simulations

2.1. Methodology – software description and limitations

This article presents a solar shading strategy parameter study for an office cell. Different shading strategies for in-between pane shading systems in various single- and two-person office spaces have been performed. Solar shadings are vital in controlling the input of solar radiation in offices; the two typologies of office cells were chosen in order to give a better representation of typical office cubicles. A room-level study was chosen in order to reduce simulation time and at the same time get a thorough investigation of the integral situation including energy demands, thermal comfort and daylight availability in the offices.

Simulations have been carried out using the numerical simulation tool COMFEN 4.1, 2012. The program is a graphical user interface tool that uses the EnergyPlus 7.0 building energy simulation program (EnergyPlus, 2011) for the underlying simulations. The software tool has been developed to carry out comparative studies of integrated energy and daylight simulations of single-zone models, for example office spaces, emphasizing detailed modelling of glazed parts of the façades. However, users should be aware of some limitations of the software, for example restrictions in the positioning of the between-glass shading layers as the default places it in the innermost cavity of a triple-pane window. This is a limiting factor if one is modelling systems where shadings might be placed in the outermost cavity. In addition to this, modelling of windows with four or more panes is not possible in combination with shading layers.

Daylight levels and the corresponding energy demand for artificial light have been studied in combination with the heating and cooling energy demands as well as energy demand for operating circulation fans in the ventilation system of the office cell.

The cooling system was sized according to the peak demand for the office cell on a typical summer day. A separate simulation of the cooling demand for the office cell was done to confirm the size of the system. The necessary air volume and flow rate of the fan was calculated. An increase in cooling demand leads to the need for a larger (more power-consuming) fan. Based on this, the energy demands for fans were considered as part of the cooling-related energy demands of the cases studied.

The window properties have been calculated using detailed spectral data of actual (real) glazing and shading layers. Input values for the various layers have been taken from the International Glazing Database (IGDB) and the Complex Glazing Database (CGDB), both of which were developed and continue to be maintained by Lawrence Berkeley National Laboratories (LBNL, 2012).

2.2. Office case description

Simulations have been performed for one- and two-person office cubicles. The main characteristics of the office cells are given in Table 1. A graphical illustration of the office cubicles is shown in Fig. 1. The windows studied are two-pane windows with a *U*-value of 1.4 W/m^2 K, three-pane windows that fulfil the Norwegian passive house standard NS 3700, *Criteria for passive houses and low energy houses – Residential buildings* (NS, 2010), with a *U*-value lower than 0.7 W/m^2 K and a state-of-the-art four-pane window with a *U*-value of 0.45 W/m^2 K. Three window-to-wall ratios (WWR) have been studied: 41%, 51% and 61%. A HVAC system that delivers the theoretical loads necessary to keep temperatures within the heating and cooling set point temperatures are used in the simulations.

Table 1
Description of office cell geometry and gains.

Single person cubicle and two-person office space	
Climate	Oslo (N 59°54′ E 10° 27′) Yearly mean temperature = 6.7 °C
Façade area (width × height)	3 × 3 m = 9 m^2
Façade *U*-value (opaque part)	0.15 W/m^2 K
Room depth	
Single-person cubicle	3.5 m
Two-person office cell	6.0 m
Heated floor area	
Single-person cubicle	10.5 m^2
Two-person office cell	18.0 m^2
Window dimensions	
2 each 1.28 × 1.43 m (width × height)	3.7 m^2 (41% WWR)
2 each 1.28 × 1.80 m (width × height)	4.6 m^2 (51% WWR)
2 each 1.28 × 2.15 m (width × height)	5.5 m^2 (61% WWR)
Window properties	2-, 3- and 4-pane window (see Table 2 for specs)
Shading strategies	11 strategies (see Table 3 for description)
Internal gains	For schedule description, see Section 2.2.2
Equipment	6 W/m^2 (NS, 2012)
Lighting (daylight continuous dimming)	8 W/m^2 (see Section 1.3.2)
Single-person cubicle	1 occupant (activity level: *office work*)
Two-person office	2 occupants (activity level: *office work*)
Daylight illumination reference point location	See Section 2.2.1

2.2.1. Daylight illumination and glare set point levels

Daylight illumination level set points for activating artificial lighting are set to 50 foot-candles, equalling 538 lux. If the illumination levels drop below this, artificial lighting is switched on. A maximum allowable GI (as described in Section 1.3.4) is set to 22. This corresponds to a level on the border between comfort and discomfort, where values lower than 22 indicate comfort. Glare indexes are based on a glare view angle perpendicular to the façade, i.e. the sensor is facing one of the side walls of the office. The sensors are placed as illustrated in Fig. 2, as per the simulation tool's default. In the two-person office space, the floor area is divided into two zones: a primary daylight zone closest to the façade and a secondary zone toward the back of the

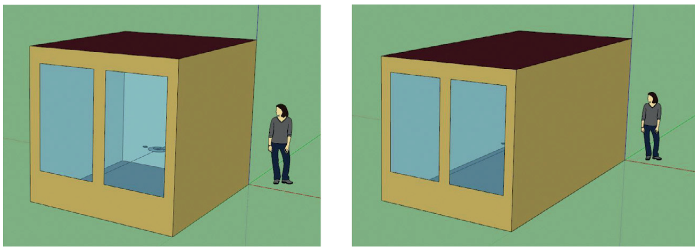

Fig. 1. Illustration of the two office cell geometries. Single-person cubicle shown on the left and two-person office cell on the right.

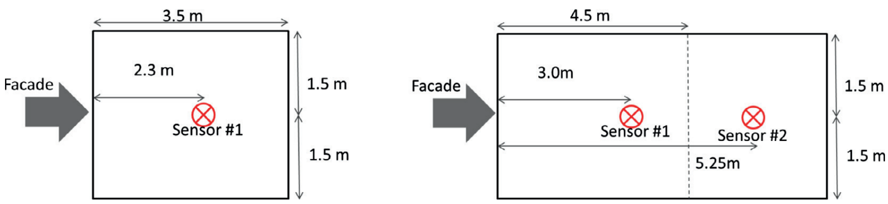

Fig. 2. On the left: illustration showing the placement of the daylight sensor in the single-person cubicle. On the right: illustration showing the placement of the daylight sensors in the two-person office space.

office space. Two sensor positions are used: sensor #1 controls the primary zone, which constitutes 75% of the floor area; sensor #2 controls the secondary zone covering the remaining 25%. As per the simulation tool's default, the primary zone sensor is positioned 2/3 of the primary daylight zone depth from the façade wall. The secondary zone sensor is by default placed in the centre of the zone. All sensors are positioned at desk height, 0.76 m above the floor. Continuous dimming functions for the artificial lighting system have been used.

Based on the discussion in Section 1.3.4, daylight illumination levels were used to assess the quality of the daylight in the rooms. Both the 100–2000 lux interval and the threshold illuminance of 300 lux were studied. This parameter was chosen rather than calculating daylight factors because it was found that it gave a better representation of actual daylight qualities in the offices studied.

2.2.2. Schedules

Default schedules for lighting, occupancy and equipment defined in the COMFEN (Mitchell et al., 2011) were used. Main operational hours are between 08.00 and 18.00 on weekdays. The schedules could not be altered in the software. Continuous lighting controls were used for the artificial light.

2.2.3. Window properties – two-, three- and four-pane windows

A double- and a triple-pane glazing unit with in-between pane venetian blinds have been studied. A four-pane window without shading has been included for further comparison. The glazing units' main characteristics of solar heat gain coefficient (SHGC), visible transmission coefficient (T_{vis}) and thermal transmittance (U-value) are shown in Table 2. The frames have been kept the same, with a U-value of 1.3 W/(m^2 K) for all the studied windows.

2.2.4. In-between pane venetian blinds – shading strategies and material properties

The shading systems studied are all a horizontal type venetian blind. Aluminium with thermal conductivity λ of 159 W/(m K) and surface emissivity of 0.9 have been used as slat material.

There are 20 predefined strategies for solar shading system controls available in COMFEN. A number of them can be customized by adjusting set point levels for solar irradiance, temperatures, etc. Six of these shading strategies, as shown in Table 3, have been chosen for further studies. A twelfth case with no shading has been included as a reference. The shading strategies were chosen in order to investigate three main principles for shading control:

- Reduce cooling demands.
- Improve visual comfort (reduce glare) and
- Reduce heat loss during the night using night-time shading.

Shading strategies 1 and 2 were chosen to represent cases where the shading is activated based on cooling demands. Strategy 3 is based on using the shading devices only for glare-reducing (i.e. daylight comfort) purposes. Strategies 4–6 were chosen in order to study if any beneficial effects of the shading devices to the thermal insulating properties of the glazing units could be found. Strategy 4 represents a case where the shading is used only during the night if there is a heating demand in the office space.

Table 2
Description of glazing units without shading layer and their key performance parameters used in the simulations.

Window	Layer-by-layer description[a]	SHGC (–)	T_{vis} (–)	U-value glazing (W/m^2 K)
2-pane window	4-29Ar-E4, $e = 0.013$, 95% argon	0.479	0.711	1.453
3-pane glazing	4-16Ar-E4-29Ar-E4, $e = 0.013$, 95% argon	0.375	0.579	0.686
4-pane glazing	4E-12Ar-4E-12Ar-4-12Ar-E4, $e = 0.013$, 95% argon	0.278	0.478	0.452

[a] The layer-by-layer description in the second column describes the following. The first number denotes the thickness of the exterior glass pane. The capital E indicates if a low-e coating is applied to the pane. An E in front of the digit indicates that the low-e coating is applied on the exterior side of the glass pane and vice versa if it is placed on the interior side. The second number (after the first hyphen) denotes the thickness (in mm) of the cavity behind the outer glass pane and if it is gas-filled. The Ar index indicates that argon is used as a gas filling. The third number (after the second hyphen) shows the thickness (and if there is any low-e coating) of the second pane. The fourth number shows the next cavity and so on for the fifth and following numbers.

Table 3
Overview of shading strategies studied.

Main shading strategy	Parameter set point	(a) Fixed slat angle	(b) Variable slat angle
No shading	–	Yes	–
Shade 1: activated if high zone air temperature	$T_{set} = 26$ °C	Yes	Yes
Shade 2: activated if high zone cooling	$P_{set} = 1$ W	Yes	Yes
Shade 3: activated if high glare	DGI = 22	Yes	–
Shade 4: activated at night if heating/off during daytime	$P_{set} = 1$ W	Yes	Yes
Shade 5: activated at night if low outside temperature/on during the day if cooling	$T_{set} = 26$ °C $P_{set} = 1$ W	Yes	Yes
Shade 6: shading activated at night if heating/on during the day if cooling	$P_{set} = 1$ W	Yes	Yes

Strategy 5 is similar but control is based on outside temperatures and includes use of shading during the daytime as well. Strategy 6 is similar to strategy 4, but here the shading is used during the day if cooling demands are also present.

In order to study the effect of variable blind angles, two cases have been studied for each of the strategies. The first case (denoted as shading strategy #a) is with a fixed slat angle where the slats are closed when shading is activated. In the second case (denoted as shading strategy #b), a cut-off strategy is used. The angle is adjusted in each simulation time-step to optimize the shade effect. A cut-off strategy like this will maximize available daylight levels. For the glare control case, only the variable slat angle option has been included. The parameter set points are shown in Table 3, where T_{set} is a temperature-based set point and P_{set} is based on incident solar radiation (in Watts).

3. Results and discussion

3.1. South-facing façades

The simulation results for the south-facing office cubicle façades are shown in Figs. 3–5 as well as in Tables 4 and 5.

The distribution of heating, cooling, lighting and fan-operation energy demands of the two-pane cases with WWR of 41% and 61% are shown in Fig. 3. The distribution for the cases with three-pane windows shows the same relative distribution for heating, cooling, lighting and fan energy demands as for the two-pane windows, and these figures are thus omitted here. Energy demand for running fans is correlated with the cooling demand, and should therefore be considered as part of the cooling-load demand. Looking at Fig. 3, one can observe that the heating demand is the dominating factor of the total demand. The combined cooling and fan load is the second largest element. Furthermore, one can see that increasing the window size from 41% to 61% in the offices increases the cooling loads, whereas the heating demands decrease slightly. This is the case for both the single-person cubicle and the two-person office. In general, one can see that a trade-off between cooling and heating-related demands is present for all shading strategies. The no-shade and shading strategy 1 cases have the lowest heating demand, but the cooling-related demands are high. Choosing one of the other strategies will lead to an increase in heating demand. This is as expected because the solar gains will be reduced.

3.1.1. Single-person cubicle offices

Even though the cooling and fan-operating demands are reduced for all strategies except for 4 and 4b, the increase in heating and lighting demands overcompensates for this and leads to a higher total energy demand. The negative impact is most pronounced for strategies 2, 2b, 6 and 6b. Thus, this research highlights that a shading system should not be installed without a thorough investigation in each case.

Fig. 4 and Table 4 shows that the potential for energy saving is dependent on office size as well as window properties. It is noted that unshaded windows are never the worst performer for any of the WWR situations. Savings potentials for two- and three-pane glazing with 41% WWR as well as three-pane glazing for the 51% and 61% cases were found to be approximately 1–2% compared with unshaded windows. For these façade configurations, the energy-saving potential for the office cell when installing shading compared to an unshaded window is insignificant.

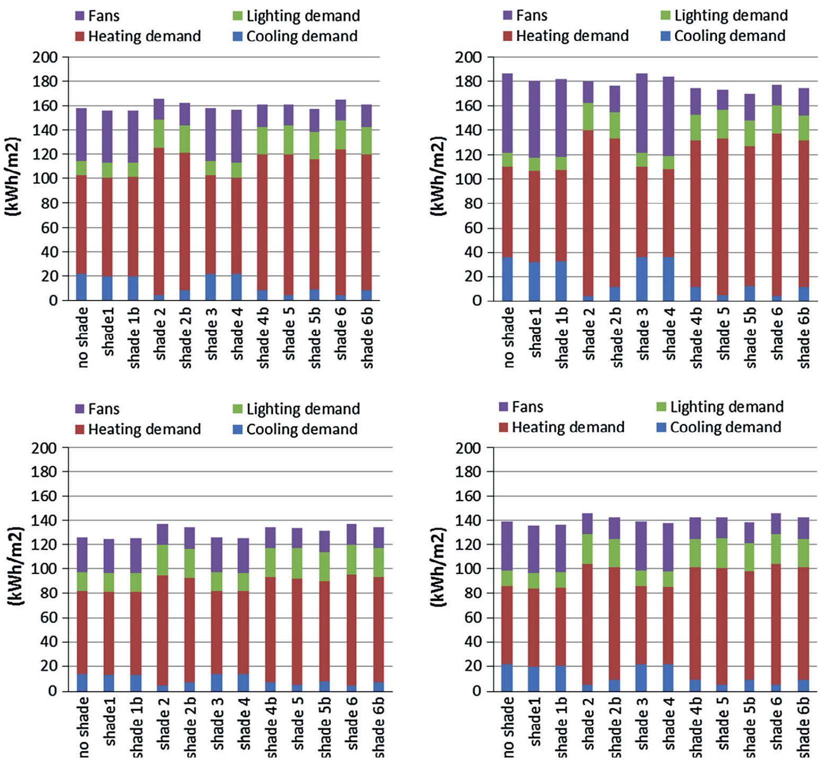

Fig. 3. Energy demand for heating, cooling, lighting and ventilation fans (kW h/m^2 heated floor area) for south-facing offices. Upper-left graph shows the two-pane 41% WWR single-person cubicle; the upper-right graph shows the two-pane 61% WWR single-person cubicle; the lower-left graph shows the two-pane 41% WWR two-person office; the lower-right graph shows the two-pane 61% WWR two-person office.

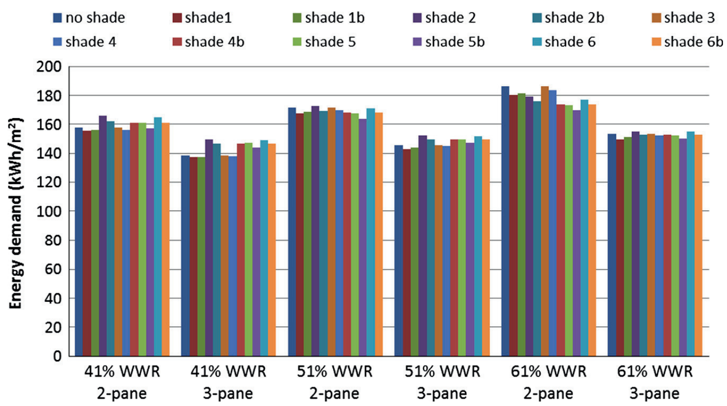

Fig. 4. Net energy demand of single-person cubicles with south-facing façades for the different shading strategies.

Two-pane glazing with a WWR of 51% show energy demand reduction potential of 5% compared to the unshaded case if shading strategy 5b is chosen. The double-pane glazing in a façade with 61% WWR shows an energy demand reduction potential of approximately 9% compared to unshaded windows when implementing a control strategy where the shading is activated during the night when temperatures are lower than 26 °C and during the day if there is a cooling demand in the office cell.

Furthermore, it can be seen that using the shading device only to reduce night-time heat losses (shading strategy 4 and 4b) has some impact. In some cases, the energy

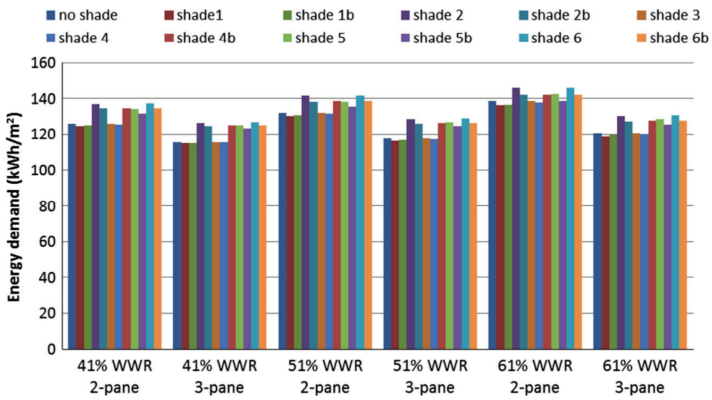

Fig. 5. Net energy demand of two-person offices with south-facing façades for the different shading strategies.

Table 4
Total net energy demand (kW h/m^2) for south-facing, single-person cubicles. The option with the lowest demand is highlighted in green; the worst-performing option is highlighted in red.

Net energy demand (kWh/m^2) for south-facing, single-person cubicle						
	41 % WWR 2-pane	41 % WWR 3-pane	51 % WWR 2-pane	51 % WWR 3-pane	61 % WWR 2-pane	61 % WWR 3-pane
No shading	158	139	172	145	186	153
Shading strategy 1	156	137	168	143	180	150
Shading strategy 1b	156	138	168	144	182	151
Shading strategy 2	166	150	173	152	179	155
Shading strategy 2b	162	146	169	150	176	153
Shading strategy 3	158	139	172	145	186	153
Shading strategy 4	156	138	170	145	184	153
Shading strategy 4b	161	146	168	150	174	153
Shading strategy 5	161	147	167	150	173	152
Shading strategy 5b	157	144	164	147	170	150
Shading strategy 6	165	150	171	152	177	155
Shading strategy 6b	161	146	168	150	174	153
4 pane, no shading	134		138		142	

demands increase; however, the largest energy demand reduction can be seen for the 61% WWR case with two-pane glazing. Here, the energy demand is reduced by 6% compared to the unshaded configuration.

The four-pane window has the lowest energy demand for all window sizes compared to any of the shaded or unshaded configurations of the two- and three-pane windows.

The use of a four-pane glazing yields significant reductions in the energy demand compared to the unshaded windows with the following configurations:

- 15% reduction compared to the two-pane 41% WWR.
- 20% reduction compared to the two-pane 51% WWR.
- 24% compared to the two-pane 61% WWR.
- 5% compared to the three-pane 51% WWR and
- 7% for the three-pane 61% WWR.

Furthermore, it was found that an erroneous choice of shading strategy can lead to an increase in energy demand. The effect is largest for the three-pane 41% WWR, which shows an increase of 8% compared to unshaded windows if shading strategies 2a, 2b, 6a or 6b are chosen.

Placing the shading units in the outermost cavity of the three-pane glazing units will probably shift the energy demands to a certain extent. This should be investigated by performing comparative studies with similar in-between shading devices placed in the outer cavity.

Table 5
Total net energy demand (kW h/m^2) for south-facing, two-person offices. The option with the lowest demand for each office type is highlighted in green; the worst-performing option is highlighted in red.

Net energy demand (kWh/m^2) for south-facing, two-person offices						
	41 % WWR 2-pane	41 % WWR 3-pane	51 % WWR 2-pane	51 % WWR 3-pane	61 % WWR 2-pane	61 % WWR 3-pane
No shading	126	116	132	118	139	121
Shading strategy 1	125	115	130	117	136	119
Shading strategy 1b	125	115	130	117	137	120
Shading strategy 2	137	126	142	128	146	130
Shading strategy 2b	134	124	138	126	142	127
Shading strategy 3	126	116	132	118	139	121
Shading strategy 4	125	115	131	117	138	120
Shading strategy 4b	135	125	139	126	142	128
Shading strategy 5	134	125	138	127	142	128
Shading strategy 5b	131	123	135	124	139	126
Shading strategy 6	137	127	142	129	146	130
Shading strategy 6b	135	125	139	126	142	128
4 pane, no shading	115		115		116	

3.1.2. Two-person offices

As can be seen from Fig. 5 and Table 5, the relative energy-saving potential on a per m^2 basis when using shading systems compared to unshaded windows is even lower for the two-person office than for the single-person cubicle. This is as expected as the relative floor to façade area increases compared to a single-person office.

For all the two- and three-pane windows and shading configurations, the savings potentials are around 1–2% and can therefore be considered insignificant.

Compared to the three-pane glazing units, upgrading to four-pane glazing yields energy savings of approximately 1–4%. The four-pane window still has the lowest energy demand for all window sizes compared to any of the shaded or unshaded configurations of the two- and three-pane windows.

As for the single-person cubicle, an erroneous choice of shading strategy will lead to an increase in the total energy demand. The effect is largest if shading strategy 6 is chosen for the three-pane 41% WWR case, with a 10% increase in energy demand compared to unshaded windows.

For the two-person office, using the shading device only to reduce night-time heat losses (shading strategy 4 and 4b) has some effect. However, in most cases it will lead to an increase in energy demand compared to the unshaded cases. Contrary to the single-person office space, no reduction was found for the 61% WWR case with two-pane glazing using shading strategy 4b; instead, the energy demand was found to increase by 2%.

The use of four-pane glazing yields significant reductions in the energy demand compared with the following configurations:

- 9% reduction for the two-pane 41% WWR.
- 13% reduction compared to the two-pane 51% WWR and
- 16% for the two-pane 61% WWR.

An increase of the window area will, for all simulation cases, lead to a higher energy demand for the offices.

3.2. North-facing façades

3.2.1. Single-person cubicles

As shown in Table 6, the simulations show that the savings potentials for these façades when shading systems are used are low. A best-case saving was found for the two-pane 61% WWR, with an energy demand reduction of 2%, which is still insignificant. Switching to four-pane glazing will yield energy demand reductions. Replacing two-pane with four-pane glazing reduces energy demands by 12–18%; replacing three-pane with four-pane glazing gives reductions close to 1%.

Furthermore, the simulations show that the wrong choice of shading strategy can lead to an energy demand increase compared to unshaded windows. The effect was found to be largest if shading strategy 2, 2b, 4, 6 or 6b is chosen for the three-pane 61% WWR case, with a 6% increase in energy demand compared to unshaded windows.

3.2.2. Two-person offices

As seen in Table 7, the simulations show that savings potentials for these façades when including shading systems are low for two-person offices with north-facing façades. A best-case saving was found for the two-pane

Table 6
Total net energy demand (kW h/m^2) for north-facing, single-person cubicles. The option with the lowest demand is highlighted in green; the worst-performing option is highlighted in red.

Net energy demand (kWh/m^2) for north-facing, single-person cubicle						
	41 % WWR 2-pane	41 % WWR 3-pane	51 % WWR 2-pane	51 % WWR 3-pane	61 % WWR 2-pane	61 % WWR 3-pane
No shading	170	152	178	155	187	159
Shading strategy 1	169	152	177	154	185	158
Shading strategy 1b	169	152	177	155	186	158
Shading strategy 2	177	158	186	162	195	167
Shading strategy 2b	177	159	187	163	195	167
Shading strategy 3	170	152	178	155	187	159
Shading strategy 4	168	152	176	154	184	157
Shading strategy 4b	176	158	184	163	192	167
Shading strategy 5	171	155	180	160	187	163
Shading strategy 5b	172	156	180	160	188	164
Shading strategy 6	175	158	184	162	192	167
Shading strategy 6b	176	158	184	163	192	167
4 pane, no shading	150		152		154	

Table 7
Total net energy demand (kW h/m^2) for north-facing, two-person offices. The option with the lowest demand for each office type is highlighted in green; the worst-performing option is highlighted in red.

North-facing façades, two-person offices						
	41 % WWR 2-pane	41 % WWR 3-pane	51 % WWR 2-pane	51 % WWR 3-pane	61 % WWR 2-pane	61 % WWR 3-pane
No shading	140	129	144	131	148	132
Shading strategy 1	139	129	143	130	147	131
Shading strategy 1b	139	129	143	130	147	132
Shading strategy 2	143	132	149	135	155	137
Shading strategy 2b	143	132	149	135	155	138
Shading strategy 3	140	129	144	131	148	132
Shading strategy 4	139	129	143	130	147	132
Shading strategy 4b	143	132	149	135	155	138
Shading strategy 5	140	130	146	133	151	136
Shading strategy 5b	140	131	146	133	151	136
Shading strategy 6	143	132	149	135	155	138
Shading strategy 6b	143	132	149	135	155	138
4 pane, no shading	127		129		130	

61% WWR, with an energy demand reduction of 1%, which is insignificant. Switching to four-pane glazing will yield energy demand reductions. Replacing two-pane with four-pane glazing reduces energy demands by 9–12%; replacing three-pane with four-pane glazing gives reductions of less than 1%.

The energy-saving potential when installing shading systems is minor. Many of the shading control strategies will yield higher energy demands than an unshaded window. The energy demand increase was found to be largest if shading strategy 2b, 4b, 6 or 6b is chosen for the three-pane 61% WWR case, with a 5% increase in energy demand.

Table 8
Key daylight and thermal comfort performance data for south-facing single-person offices with two-pane glazing. The unshaded and the shading alternative with the lowest energy demand for each of the WWRs are shown.

	41% WWR		51% WWR		61% WWR	
	Unshaded	Best performer 1b	Unshaded	Best performer 5b	Unshaded	Best performer 5
Average GI (GI_{avg})	5	4	5	1	5	1
Hours when GI > 22	115	113	115	17	115	15
Hours when illumination > 300 lux	2613	2476	2926	681	3108	924
Hours when daylight illumination is in the range of 100–2000 lux	3086	2997	2790	1954	2582	1347
Average illumination level due to daylight (lux)	487	462	680	144	904	165
Thermal comfort, Fanger average PPD (%)	18	18	18	21	18	25

3.3. Daylight, glare and thermal comfort

3.3.1. South-facing façades

Table 8 shows key lighting data for south-facing single-person cubicles with two-pane glazing. The unshaded façades are compared to the shading strategy with the lowest energy demand. It is obvious that the introduction of a shading system that minimizes energy demands will influence the daylight and glare levels in the offices. The effects are most pronounced for the largest WWR. The effects are, however, twofold: the GI will be reduced and the hours when the GI is above 22 are reduced significantly. For the 61% WWR, the number of hours when glare is above the limit of 22 will be reduced by 90% when installing a shading system. However, the average yearly daylight levels will be reduced to approximately 80% compared to an office with unshaded windows.

The thermal comfort is not significantly altered as a function of the shading strategies, as shown in Table 8. The PPD is constant regardless of window size and shading strategy except for one case. The case where a notable change occurs in the PPD is the 61% WWR case. The PPD increases from 18% to 25% when switching from unshaded windows to shading strategy 5. The increase in the PPD when switching to shaded windows mainly occurs in the period from early May to mid-September. This is somewhat counter-intuitive as one should expect that adding shading would improve the thermal comfort during the warm period of the year due to better control of solar insolation. The algorithm used for assessing thermal comfort according to the Fanger method is a function of the mean radiant and air temperature, among other elements (EnergyPlus, 2012). It was found that the yearly average mean radiant temperature for the office using shades was higher than for an unshaded office. This is not as expected and is caused by higher window interior surface temperatures with blinds closed. It is likely a result of how the software tool treats the absorption and reflectance properties of the opaque slats in the shading device. It seems that absorption of solar energy in the shading slats is overestimated and gives an improbable temperature increase. This will spread further inwards in the glazing unit and the temperature of the interior glass pane will ultimately increase. One should therefore treat the thermal comfort simulation results using Energy Plus ver. 7.0 with care and any conclusions without further investigations of the algorithm could not be drawn. Measurements on systems should be carried out in order to verify the behaviour of such shading systems.

3.3.2. North-facing façades

Simulations show that north-facing offices will not meet current standards and demands for daylight levels. The best-case scenario, with the highest daylight levels, is with an unshaded two-pane glazing and a WWR of 61%. This particular office cell will have an average daylight illumination level at sensor 1 of 236 lux. Furthermore, it was found that the daylight illumination level is higher than 300 lux during 2775 h of the year for this configuration.

The simulations also show that for north-facing façades, glare issues will never be a problem due to direct solar radiation. This is the case even for an unshaded façade with two-pane glazing and a WWR of 61%, which has a maximum GI of 12. Reflections from neighbouring buildings could, however, be a problem. Shading devices designed only for glare reduction should therefore be considered in such cases.

4. Discussion and conclusions

Simulations of a number of shading strategies have been performed for south- and north-facing office cubicles with varying floor areas, window sizes and window parameters. Energy demands for heating, cooling, lighting and ventilation fans have been assessed. The simulations show that the choice of shading strategy can have an impact on the energy demand of the offices. Depending on strategy, the energy demand can either increase or decrease compared to an unshaded one- or two-person office cubicle.

North-facing offices were found to have larger energy demands than south-facing offices, mainly due to higher heating demands. Lighting energy demand is also slightly higher for north-facing offices. The use of shading systems has insignificant potential for reduction of energy demands on north-facing façades. On the contrary, it can potentially lead to an increase in energy demands of as much as 5% if an improper strategy is used. Shading systems should therefore not be used on north-facing façades of small- or medium-sized office cubicles. Using four-pane glazing will, however, reduce the energy demand compared to windows with two- or three-pane glazing. Other aspects such as color rendering due to a thick glass layer must be addressed in order to ensure good visual quality of the spaces. Using low-iron glass could be one of the technical solutions for this.

The simulations also show that glare issues will never be a problem for north-facing façades. The GI level for any of the north-facing façades never exceeded 12.

In contrast to the north-facing façades, the results show that there is potential to reduce energy demands for the south-facing façades. Energy demand reductions can be as large as 9% if the right shading strategy is chosen. However, as for the north-facing offices, it was found that improper use of shading systems will lead to an increase of the total energy demand. This increase in energy demand can be as high as 10%.

Thus, it can be concluded that automatically controlled shading systems can reduce the energy demands of south-facing, small office cubicles, but they should not be installed without a thorough investigation in each single case.

Upgrading to four-pane glazing will always have a beneficial impact on the energy demand compared to two- and three-pane glazing. Energy demand reductions can be as high as 20% if two-pane glazing is replaced with four panes. If a three-pane window is interchanged with a four-pane glazing unit, energy demand reductions were found to be as high as 7%. Glare problems must however be addressed and reduced to an acceptable level; this will not be achieved with unshaded façades. The location of glare-reducing measures is not limited to in-between glazing pane shading units; both internal and external shading devices can be utilized.

5. Further work

Simulations have been performed for shading systems placed in the innermost cavity of the glazing units. Future studies should investigate the effects of shading systems placed in the outermost or other internal cavities of the glazing units as well as externally placed shading systems. Four-pane glazing in combination with in-between or external shading systems should also be studied. Further studies should also be carried out where the performance of shading systems is assessed on the whole building level. Optimization algorithms for thermal as well as optical performance of shading systems should be established in order to make guidelines that are useable in the early stage planning of offices and office façades.

Measurements of component performance as well as room and whole building performance should be carried out with the purpose of validating the simulations.

The thermal comfort situation for different shading strategies is of utmost importance for a building. The simulation results for thermal comfort were ambiguous and should therefore be treated with care and further investigation of simulation procedures should be completed.

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Scientific paper IV

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Possibilities for characterization of a PCM window system using large scale measurements

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Possibilities for characterization of a PCM window system using large scale measurements

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Abstract

The introduction of dynamic envelope components and systems can have a significant reduction effect on heating and cooling demands. In addition, it can contribute to reduce the energy demand for artificial lighting by better utilization of daylight.

One of these promising technologies is Phase Change Materials (PCM). Here, the latent heat storage potential of the transition between solid and liquid state of a material is exploited to increase the thermal mass of the component. A PCM layer incorporated in a transparent component can increase the possibilities to harvest energy from solar radiation by reducing the heating/cooling demand and still allowing the utilization of daylight.

Measurements have been performed on a state-of-the-art, commercially available window that integrates PCM using a large scale climate simulator. The glazing unit consists of a four-pane glazing with an integrated layer that dynamically controls the solar transmittance (prismatic glass) in the outer glazing cavity. The innermost cavity is filled with a PCM, contained in transparent plastic containers.

When dynamic components are incorporated in the building envelope, it makes the characterization of static performance (e.g. the thermal transmittance, *U*-value; the solar heat gain coefficient) insufficient in giving the full picture regarding the performance of the component in question.

This article presents a series of preliminary measurements, and the related methodologies, carried out on a window with incorporated PCM. The tests have been carried out using several test cycles comprised of temperature and solar radiation cycling, where the aim has been to delve deeper into the possibilities for the characterization of dynamic building envelope components by full scale testing in a climate simulator, showing potentials and limitations of this approach and measurement facility.

It was found that even for temperatures similar to a warm day in Nordic climate, the potential latent heat storage capacity of the PCM was fully activated. Long periods of sun combined with high exterior temperatures are needed.

Keywords: Window; Façade; Phase change; PCM; Experimental

1. Introduction

1.1. Technology overview

Based on the recommendations given in IEA ECBCS Annex 44 and the "Kyoto Pyramid" (IEA, 2011), combined with the fact that windows contribute to a substantial part of

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the heat losses and gains, a further investigation on the possibilities of reducing the energy demand related to glazed and/or translucent parts of the facades is necessary.

In recent years there has been an increasing interest in and amount of research carried out regarding fairly new technologies like Phase Change Materials (PCM). A PCM in a building context is a material that has a melting point in the region close to the comfort or operational temperature in the building where it is adopted. The latent heat storage potential in the phase transition between liquid and solid state can thus be utilized as heat storage and shows a favorable behavior in terms of increasing the thermal inertia of the system. The raw materials used to produce PCM's can be divided in three main groups, eutectic, organic and in-organic materials (Baetens et al., 2010). For the use of PCM in windows, paraffin based, organic materials are the most interesting, since they are transparent in the liquid state and translucent in the solid state.

Some studies concerning PCM in combination with glazing have previously been performed. These range back to 1997, with a study of the PCM layer coupled with a transparent insulated material (Manz et al., 1997). The aim of including a PCM layer into a transparent system is to collect (a large part of) the NIR solar radiation (that does not contribute to daylight) within the PCM layer itself and letting (the largest part of) the visible solar radiation enter the indoor environment, thus still allowing natural light exploitation for daylighting purposes. This behavior is achieved thanks to the highly selective optical properties of some PCM, e.g. paraffin wax. An investigation of the optical properties of PCM layers in combination with glazed layers was carried out, by means of a Large Integrating Sphere facility, by Goia et al. (2012), who characterized different thicknesses of the PCM and the angular-dependence of the coefficients.

The use of PCM as moveable shutters was studied by Ismail and Henriquez (2001). Here, PCM are pumped to and from a storage tank underneath the window. The authors conclude that a PCM filled window is thermally more effective than an air-filled window as it filters out thermal radiation which in term reduces heat gains or losses. Weinläder et al. (2005) performed measurements on a double glazing with a PCM acting as a third (internal) layer to the glazing unit. The authors found that a reduced heat loss compared to the double-glazing unit is mainly due to the additional cavity behind the PCM. There was also found a slight shift in peak energy flows when using the PCM, but the authors concluded that if the heat gains of a double glazing (higher during mid-day) can be stored it might overcompensate the high heat losses of this system. However, the addition of PCM has a positive effect on thermal comfort by dampening the extreme temperatures during mid-day and night.

A study where PCM was used for latent heat storage in an internal slat-blind shading device (Weinlaeder et al., 2011), concludes that there is a substantial cooling potential during summer, and also some benefits during wintertime, compared to a conventional material blind. Whereas, the PCM used here are not transparent, it is used in combination with a window, thus making it part of a transparent component. Likewise, a numerical simulation study for externally placed shutters with PCM (Alawadhi, 2012), conclude that the heat gain through the window can be significantly reduced when mounting shutters with PCM compared to an un-shaded window. A comparison of two-pane windows with a gas-filled cavity and a PCM filled cavity was performed by Ismail et al. (2008). Goia et al. performed an experimental analysis on a double glazing system with paraffin wax, by means of an outdoor test cell facility located in a temperate sub-continental climate (2010). Implications of this system on thermal comfort condition were also investigated starting from experimental data (Goia et al., 2013), and physical–mathematical models (Goia et al. 2012) for simulating PCM glazing systems were developed too. Recently, Gowreesunker et al. (2013) analyzed the optical and thermal properties of a small scale PCM-glazed unit, assessing its performance by a combined experimental–numerical analysis. The investigation focused on the relationships that describe the extinction, scattering and absorption coefficients within the phase change region, validated in a numerical CFD model.

1.2. Scope of work and possible outcome

Performing measurements on dynamic systems, like the PCM glazing, is extremely relevant. The complex interaction of solar radiation and phase change has a complicating effect on the physical behavior of such a system. Characterizations that make use of only analytical and numerical tools are well known to be difficult and subject to experimental validation. Full scale testing can thus serve as validation support for the theoretical models that are being developed. An example of this procedure can be found in Cao et al. (2010). The measurements carried out for an opaque wall incorporating PCM presented in this article have been used for validation of a numerical model (Tabares-Velasco et al., 2012). The use of a full scale climate simulator, where temperatures and solar irradiance levels can be dynamically regulated and controlled, increases the possibilities to deepen the investigation on the behavior of a translucent component under defined environmental conditions.

1.3. The PCM glazing

Measurements have been carried out on a commercially available glazing system with an integrated prismatic solar reflector and a PCM filled cavity. The producers have not stated the amount of PCM in the window, but the thickness of the PCM encasings were measured to be approximately 23 mm thick. The type of glazing system has been used in several existing buildings, primarily in Switzerland. The PCM glazing is often combined with standard windows in the façade, as shown in Fig. 1. The window is a 1.2 by 1.2 m large window which consists of a four-pane glazing package A solar reflection device, i.e. a prismatic glass (Christoffers, 1996) is placed in the outermost cavity, the second is argon-filled cavity, and the innermost, third cavity is filled with a polycarbonate encapsulated PCM. A cross-section of the window is shown in Fig. 2. The window optical and thermal properties are shown in Table 1.

2. Test method and measuring equipment

2.1. The climate simulator

In this work, measurements have been performed on a state-of-the-art glazing system incorporating PCM using a climate simulator. The climate simulator is an apparatus in which the climatic conditions on both sides of a building component sample can be dynamically controlled.

The climate simulator is made up of two chambers, separated by the sample. The left side, as shown in Fig. 3, is used to simulate exterior conditions. In this chamber, the temperature can be controlled from −20 to +80 °C. Relative humidity levels can be varied between 20% and 95%. In addition, both water (rain) and solar radiation can be applied. The solar radiation is supplied with nine xenon lamps. The lamps have been calibrated in order to produce a maximum, nominal solar radiation level of 1 kW/m^2 integrated over the full spectrum, evenly distributed over the

Fig. 1. On the left; External view of building with a combination of standard windows and PCM-windows (Architekten, 2000a). On the right; internal view of standard windows and PCM-windows in combination, PCM being the semi-translucent elements on the sides of the windows (Architekten, 2000b, 2004.

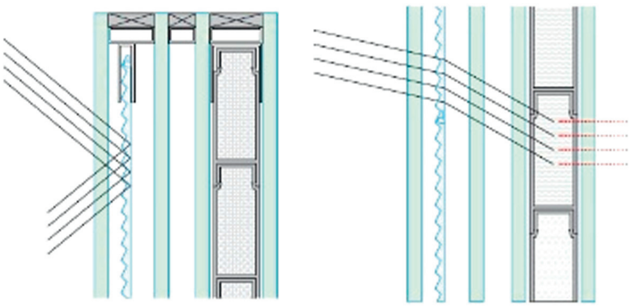

Fig. 2. Vertical cross sections of the PCM window. (GlassX, 2012). The figures illustrate the angular properties of the solar reflector in the outer cavity, where radiation with high incidence angles (typical summer days) are reflected and low-angle incident radiation (typical winter days) is let through.

Table 1
Declared and measured thermal and optical values of the PCM glazing.(GlassX, 2012; Salvesen et al., 2012). The value of α in the measured values in columns, show the angle of incident light.

	Declared values (GlassX, 2012)			Measured visual transmittance values (Salvesen et al., 2012)		
	U-value (W/m^{2}K)	Solar heat gain coefficient (*g*-value)	Visual transmittance (Tvis)	Direct – diffuse $\alpha = 0$	Direct – diffuse $\alpha = 30$	Diffuse – diffuse
Solid state	0.5	0.33 ± 4%	0.08–0.24 (±3%)	0.21	0.19	0.17
Liquid state		0.37 ± 4%	0.12–0.44 (±3%)			

entire sample area and with a wave-length distribution similar to that of the sun. The lamp array is placed with a perpendicular distance to the test sample of 1 m. All lamps can be switched on and off individually and the effect can be varied step-less down to 50% of the maximum level. The lamps produce a homogenous irradiance level over the entire sample, thus making studies of angular properties more difficult. The other, right, side on Photo 2 represents the interior side of the construction. Here, the temperature can be varied within a range of +5 to +50 °C. Relative humidity levels can be varied between 20% and 95%. The air temperatures in both adjacent test chambers are based on temperatures measured in the exhaust air from their respective chamber, and are thus representative of the average air temperature inside each thermostatic chamber. Concerns may rise as far as the air temperature in front of the lamps array, since the xenon lamps may warm up the air layer that borders with the solar simulator. It is important to stress that the exact measurement of the temperature in the air gap between the lamps array and the sample can be difficultly assessed, since thermal sensor readings may be deeply influenced by the short-wave radiant flux, and thus result in inaccurate measured values. The air gap overheating phenomenon is reduced to the minimum extent by the following measures: the lamps array is placed far enough from the sample (1 m) in order to have a significant air layer between the lamps and the sample; the air-change rate in the chamber that hosts the solar simulator was kept at a high level in order to ensure sufficient ventilation in the gap between the lamps and the sample.

2.2. Instrumentation

Heat flows, temperatures and solar radiation levels were continuously monitored and logged during the experiment. Temperatures were measured using type T thermocouples in five positions on each side of the test specimen. The T-type thermocouples have a declared uncertainty of ±2%. Heat fluxes were measured using four heat flow meters (HFM), whose nominal measurement error provided by the producer is ±5%. Solar radiation levels, both on the "outdoor-side" of the sample (impinging solar flux) and on the "indoor-side" of the sample (transmitted solar flux) were measured on the vertical plane, in the 300–3000 nm spectral range using two pyranometers. The nominal accuracy of this sensor is ±5%. The solar radiation levels were measured using a pyranometer placed on the lower right (seen from the exterior side) side of the specimen 10 cm from the surface, see Photo 3. On the interior side, an identical pyranometer was placed in the center axis of the test specimen approximately 1 m from the interior surface so that no direct shading from HFM or other sensors affected the pyranometer.

Fig. 3. The climate simulator used for the PCM-glazing measurements.

Due to different absorptivity, emissivity and surface properties of the thermocouples and HFM compared to the glazing unit, shielding from direct solar radiation was found to be necessary in order to reduce the influence of the short-wave radiant flux on the sensor readings. A rigid, reflective aluminum foil was placed as a radiation shield over the sensors leaving a 2 cm wide ventilated cavity between the foil and the sensor, as shown in Fig. 4. This was done to avoid overheating of the sensors due to direct radiation. A similar procedure with shielding of sensors has previously been applied with success in previous studies (Corgnati et al., 2007; Zanghirella et al. 2007; Goia et al., 2010).

2.3. Measurement test cycles

Although the experimental facility is able to dynamically change the outdoor (and indoor) boundary conditions, tests carried out in this part of the research activity have focused on stationary boundary conditions. In one aspect, this approach will not allow the most relevant (dynamic) features of advanced systems to be fully exploited and evaluated. It will, however, give fundamental knowledge of the thermophysical and optical behavior of such systems. This can later be used to plan a more dynamic measurement campaign. Table 2 shows the overview of all test cycles performed. The table describes the interior- and exterior temperature, the average level of solar irradiance across the sample and the duration of each test cycle. The tests were run with solar irradiance levels and durations as stated in Table 2. Between each test cycle the solar irradiance level was set to zero for a set period.

In the experiments carried out in this work, the main focus is placed on the influence of solar irradiance on the PCM layer, combining different short-wave radiation fluxes with different thermal gradients and temperature levels. In particular, Test 1–6 exclude the effect of heat transmission due to thermal gradient between the outdoor and the indoor chamber, and allow deep analysis to be done on the influence of solar irradiance alone. On the contrary, Test 7–9 present a thermal gradient (10 °C) between the two chambers and short-wave radiation pulses, giving pictures of combined mechanisms due to different stresses.

Fig. 4. The picture on the left shows details of the radiation shielding of HFM's using a rigid, reflective aluminum foil. The picture on the right gives an overview of the instrumentation of the PCM window, showing thermocouples and HFM's shielded with aluminum foil placed at two levels (up and down). The pyranometer is visible in the lower right corner of the PCM window.

Table 2
Test cycle descriptions.

Test #	Indoor air temperature (°C)	Outdoor air temperature (°C)	Solar irradiance/ duration	Aim of study
1	24	24	1000 W/m^2/1 h	Study the influence of the solar radiation in a temperature range close to the
2	24	24	1000 W/m^2/2 h	transition phase; no contribution of thermal gradient between outdoors and
3	24	24	1000 W/m^2/4 h	indoors; conditions similar to summer period (with no temperature swing)
4	24	24	500 W/m^2/2 h	Study the influence of the solar radiation in a temperature range close to the
5	24	24	500 W/m^2/4 h	transition phase; analysis of the influence of the density of solar irradiance (500 vs.
6	24	24	500 W/m^2/8 h	1000 W/m2) on the behavior of the PCM layer (same irradiation of test 1–3)
7	20	10*	1000 W/m^2/2 h	Study the influence of the solar radiation in a temperature range far from the
8	20	10*	1000 W/m^2/4 h	transition phase; contribution of the thermal gradient between outdoors and
9	20	10*	1000 W/m^2/8 h	indoors; conditions similar to a winter situation

3. Results

3.1. General discussion

As already mentioned, the introduction of dynamic properties in façade components makes characterizing them a complex task. Traditional static parameters, like the thermal transmittance (*U*-value) and solar heat gain coefficient, are unable to fully describe the thermal performance and their significance becomes questionable too.

The measurements performed points out some of the potential benefits of dynamic systems like this. It also shed light on some of the challenges encountered in the measurement procedure.

3.2. Solar irradiance and transmittance measurements

Measurements to assess the direct solar transmittance level of the system have been carried out. Table 3 shows the irradiance levels on the exterior- and interior side of the climate simulator as well as the solar transmittance of the PCM-window. An example graph of the measured irradiance levels is shown in Fig. 5. Table 3 shows fairly consistent results for the irradiance level differences between the exterior and interior, which is in principle what the solar transmittance shown here is. A slightly lower value is recorded when an outdoor solar irradiance of 500 W/m^2 was employed (tests 4–7). When 500 W/m^2 was employed the power of the lamps was reduced to 50% of max nominal power. The reduction of output level leads to a small change in the solar spectrum of the lamps. This is likely the cause for the reduced measured solar transmission values for the series with 500 W/m^2. The measured value of the GlassX window is sensibly lower than that measured in previous experiments, and this can be explained considering the more complex layer structure of the specimen under test – that includes a prismatic glass, polycarbonate containers and a much thicker PCM layer.

There seems to be no relevant difference in the direct solar transmittance between the solid state and the liquid state (which is reached, at least partially, in Test 3). This behavior can also be explained considering the complex structure of the glazing, where the optical properties of the PCM layer alone have a much lower impact on the total behavior than other, simpler configuration investigated in the literature (Goia et al. 2012; Gowreesunker et al., 2013).

Table 3
Solar irradiance levels on interior and exterior sides (W/m^2K) of the sample and the interior irradiance level relative to the exterior irradiance level.

Test cycle nr	Exterior irradiance (W/m^2)	Interior irradiance (W/m^2)	Solar transmittance (−)
1	1115	149	0.13
2	1225	154	0.13
3	1241	164	0.13
4	478	53	0.11
5	488	54	0.11
6	486	56	0.11
7	1285	197	0.15
8	1236	174	0.14
9	1156	161	0.14

3.3. Surface temperature measurements

The measurements performed in test series 1–3, were carried out with the highest solar radiation level of all the series. For the first two cycles, as shown in Fig. 6, it is possible to see that the temperature propagation for both the interior and exterior measuring points follow a smooth exponential development, thus indicating that the phase change dynamics of the glazing have been activated. However, for the third cycle where the duration of the solar stress was four hours, it is possible to verify that the temperature increase of the interior surface has a larger gradient for the latter part of the period. This, more linear temperature propagation indicates that the phase transition temperature of the PCM has been reached and the internal temperature of the PCM will increase undisturbed by the latent energy storage effects of the phase transition. When the lamps are turned off and solar stress comes to an end, it can be observed that the instant temperature drop is fast, but that the latter temperature decrease follows a less steep evolution, further confirming that the thermal inertia given by the latent heat of fusion of the PCM has been fully activated. Furthermore, it can be derived from Fig. 3 that the upper and lower thermocouple shows different values. This can be explained considering the temperature stratification within the specimen itself, that is a quite common feature in glazing systems that contains cavities filled with air or other gases (Manz, 2003). It is also possible to relate this phenomenon to an air-temperature stratification in the gap between the sample and the solar simulator, although it has been already discussed that, because of the structure of the facility measurement, this aspect is (very likely) reduced to the minimum extent – but cannot be completely ruled out. The temperature stratification is so relevant that, in Test 3, the PCM contained in the upper part of the window completes the phase transition and is in liquid state when the solar simulator is turned off, while that contained in the lower part of the window is still in the transition phase. It is worth mentioning that the stratification phenomenon seems to be enhanced when a higher solar flux impinges on the window (Tests 1–3 and 7–9), with a temperature difference along the height of the window of more than 2 °C.

From Figs. 7 and 8 it is possible to observe that the highest interior temperatures reached are approximately

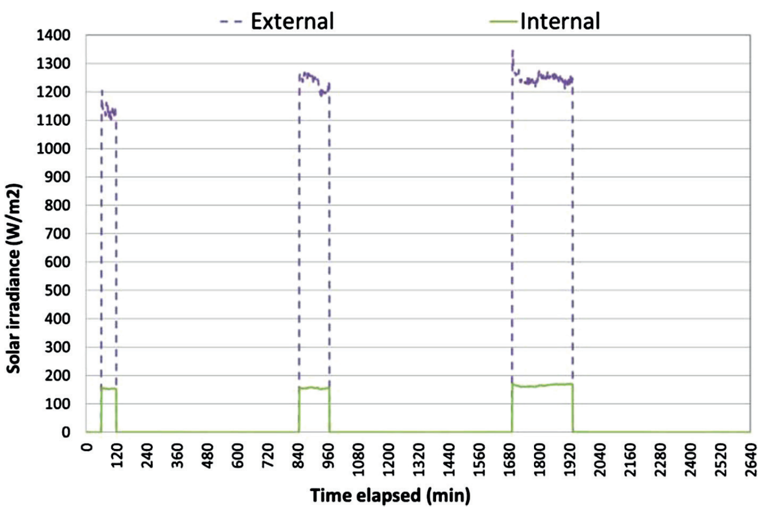

Fig. 5. Solar irradiance level measurements for test cycles 1–3.

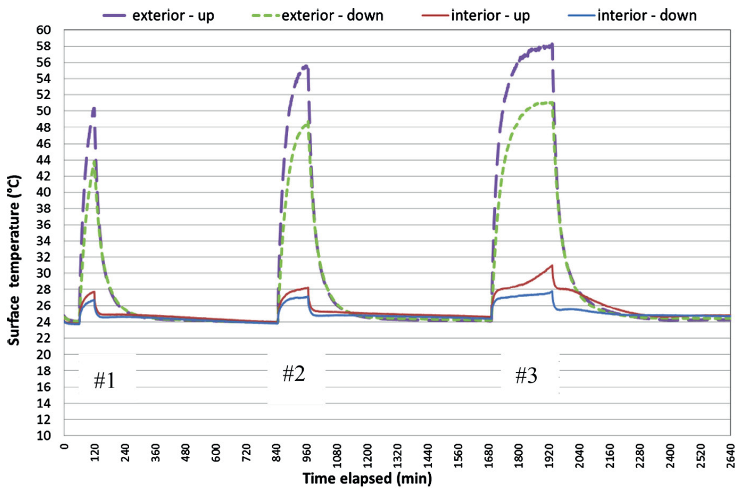

Fig. 6. Surface temperature plots for test series 1–3. Solar radiation level 1000 W/m^2 and interior and exterior temperature 24 °C.

26–27 °C. The temperature development follows an exponential curve for all the measurements and it is clear that the temperature range for phase change of the PCM is reached.

The difference in the temperature of the window surface before the solar stimulus is applied and soon after it comes to an end is a measure of the energy stored within the glazing system (and in the PCM layer especially). This temperature difference reaches more than 4 °C when the PCM completes the phase change (Test 3, upper part), and up to a bit less than 2 °C when the solid-to-liquid transition is not fully exploited.

Tests 7–9 give more information about the combined effect of thermal gradient and solar irradiation. It is possible to see that the thermal energy stored in the glazing systems is reduced compared to a reference situation (Tests 1–3), where there is no heat loss toward the outdoor chamber – under these circumstance, the maximum temperature difference in the window surface before and after the solar pulses is lower than 3 °C (Test 9). Furthermore, one can see that steady state of the system is not reached during the eight hour relaxation time between solar exposures for the measurements in Fig. 5. This is an indirect measurement of the elevated thermal inertia of the system.

4. Discussion and future work

The preliminary measurements presented in this paper allow some important consideration for future experimental campaign to be drawn.

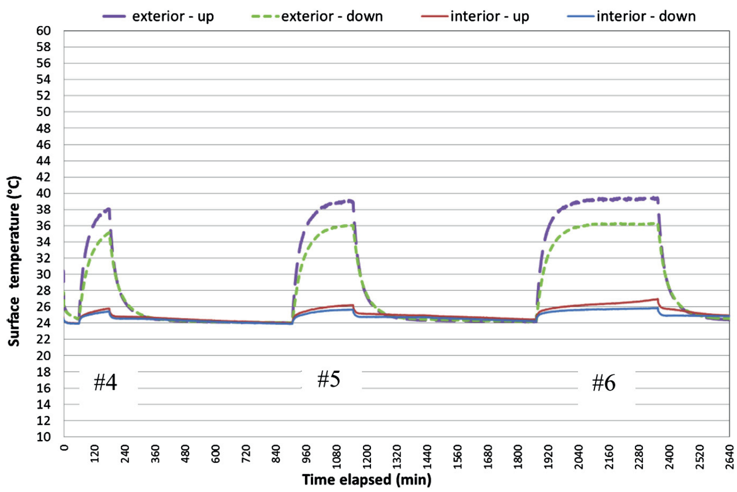

Fig. 7. Surface temperature plots for test series 4–6. Solar radiation level 500 W/m^2. Interior and exterior temperature 24 °C.

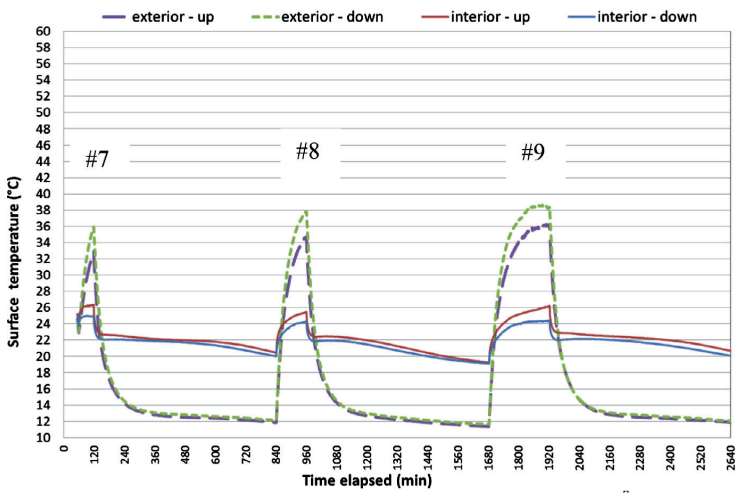

Fig. 8. Surface temperature plots for test series 7–9. Solar radiation level 1000 W/m^2. Interior temperature 24 °C and exterior temperature 10 °C.

The temperature stratification on the window is more significant than expected, and probably to be related to the highly non-linear behavior of the PCM layer – the stratification is enhanced by the fact that in some areas the PCM completes the melting process, while in other it stays in a solid–liquid mixture during the whole test. This makes it necessary to measure the surface temperature in several places in order to have a full picture of the window thermal behavior.

The very high thermal inertia of the system prevents it reaching a steady state condition if only 12 h are left between two solar stimuli – this phenomenon is especially enhanced when solar stress and thermal gradient stress are coupled, In future analysis, longer relaxation periods need thus to be employed – at least 24 h.

The window were instrumented with two heat flow meters (HFM) on each side of the glazing unit with the goal of measuring the thermal transmittance of the glazing unit. These measurements were performed in separate test series for both liquid and solid state of the PCM. No solar radiation was applied in these series. The measurements were, however, not reliable and gave large variations. After the test had been performed, it was discovered that the lower HFM on the exterior side of the sample had detached from the window surface and that the upper exterior HFM had curved, thus creating a air cavity between the sample and the HFM. This was probably caused by thermal stresses to the HFM. In addition, the opposing HFM's placed internally and externally showed incoherent values. Hence, proper thermal transmittance measurements using a hot box or similar should be performed in order to get reliable results.

A limitation in the study is given by the solar simulator structure. It is not able to replicate the full optical characteristics of the solar irradiance (i.e. direct component plus indirect irradiance). Due to the particular technology under investigation, that includes a prismatic glass, and thus has a high dependence on the geometry of the solar radiation, the investigations that can be carried out by means of this measurement facility are partial. Unfortunately, it is not possible to solve this issue with the available test rig. In order to overcome this limitation, a measurement campaign using an outdoor test cell facility is planned.

Furthermore, the measurements presented in this article are presently limited to steady state conditions. They should be expanded with test cycles imitating real climate data and for a better understanding of the behavior. Conventional systems (e.g. a triple glazed unit) will be measured using the same cycles for ease of comparison. Finally, more reliable *U*-value measurements will also be carried out.

5. Conclusions

Measurements have been performed on a four-pane window system incorporating a solar reflector in the outermost cavity and a PCM layer in the innermost cavity. Both static parameters as well as characterization of the dynamic response of the system have been studied.

Solar irradiance levels were measured on the interior and exterior sides of the sample, yielding consistent numbers for the amount of radiation transmitted through the sample, regardless the state of aggregation of the PCM. This value gives one of the components of the SHGC for the system. The value does not, however, take into account the factors of heat transport due to other transfer mechanisms induced by the effect the solar radiation has on the surface temperatures and gradients over the sample cross-section. These heat transfer effects will be the subject of future studies. It was found that even for temperatures similar to a warm day in Nordic climate, the potential latent heat storage capacity of the PCM was fully activated. Long periods of sun combined with high exterior temperatures are needed. This suggests that lower melting point temperatures for the PCM could be considered for cold climates in order for a better utilization of the latent heat storage potential.

For systems with high thermal inertia, like the PCM-based system tested here, sufficient time interval between periodic cycling of stresses must be ensured. Measurements showed that a period of, in this case, 10–12 h between applications of solar radiation was not enough to ensure the complete stabilization of temperatures and steady state conditions between the stress cycles.

Acknowledgements

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Scientific paper V

Steinar Grynning, Cezary Misiopecki, Sivert Uvsløkk, Berit Time, and Arild Gustavsen,

Thermal performance of in-between shading systems in multilayer glazing units
– Hot-box measurements and numerical simulations

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Thermal performance of in-between shading systems in multilayer glazing units: Hot-box measurements and numerical simulations

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Abstract

Shading systems are widely used, also in Nordic climates, in conjunction with glazed facade in office buildings. The primary functions of the solar shading devices are to control solar gains leading to cooling needs during operational hours and reduction of discomfort caused by glare. A secondary property of shading devices incorporated in glazing units is that they can be utilized as an additional layer in the glazing unit when the shading device is deployed. This can improve the thermal transmittance value (U-value) of the windows. It can be deployed during night-time or in periods when a blocked view does not have any consequences for the users of the building. This article presents hot-box measurements of thermal transmittance values (U-values) performed for three insulated glazing units with integrated in-between pane shading systems. The shading devices are venetian-type blinds with horizontal aluminum slats. The windows with double- and triple-pane glazing units have motorized blinds. The window with a 4-pane glazing has a manually operated blind placed in an external coupled cavity.

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The measurements are compared to numerical simulations using the WINDOW and THERM simulation tools. The results showed that only minor reductions of U-values of the glazing units were obtained as function of shading system operation. It was, however, found that the introduction of shading devices in the window cavities will increase the total U-value of the window due to thermal bridging effects caused by shading device motor and the aluminium slats of the blinds. coupled cavity.

Keywords
Window, glazing, shading, insulated glazing unit, venetian blinds, hot-box, laboratory

Introduction

General

Shading systems are widely used, also in Nordic climates, in conjunction with glazed facade in office buildings, where the internal gains are relatively large. The primary functions of the solar shading devices are to reduce solar gains which will lead to a cooling need during operational hours and reduce discomforting glare from. A secondary property of shading devices which are incorporated in the glazing units is that they, to a certain extent, can be utilized as an additional layer in the glazing unit when the shading device is deployed. This can in turn improve the thermal transmittance value (U-value) of the windows. It can be deployed during night-time or in periods when a blocked view does not have any consequences for the users of the building. The angle of the slats will also influence the effect on the U-value if venetian-type blinds are being used.

The optical performance and properties of shading systems have previously been studied to a large extent, but possible benefits of the thermal insulation of the combined glazing and shading systems have, however, not been given much attention. The possibility of dynamically controlling the shading devices might give an energy saving potential due to the control of both solar transmission levels and the aforementioned thermal insulation effects (i.e. altering the U-value of the component).

Throughout the literature, several definitions of the angular positioning of venetian blind slats can be found. In this work, a common definition is given as described in Figure 1. A configuration with horizontal blinds has a corresponding slat angle $\alpha = 0°$. When the slats are tilted with the top of the slat facing inwards, a positive angle is defined, that is, a vertical position with the top of the slat towards the interior side is defined as having a slat angle $\alpha = 90°$. Correspondingly, a vertical slat with the top facing the exterior side is defined as having a slat angle $\alpha = -90°$.

Former studies and relevant standards

For insulated glazing units (IGUs), determination of thermal and optical properties is done according to ISO 15099:2003 (2003) –*Thermal performance of windows,*

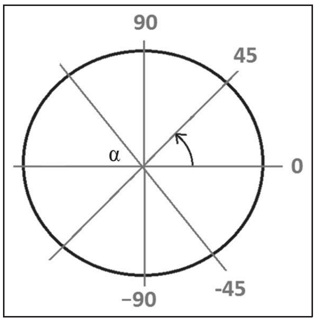

Figure 1. Venetian blind slat angle definition. Horizontal slats are defined as having a slat angle $\alpha = 0°$. Vertical slats with top of the slat facing the interior are defined as having a slat angle $\alpha = 90°$. Vertical slats with top of the slat facing the exterior are defined as having a slat angle $\alpha = -90°$.

doors and shading devices – detailed calculations. Calculation procedures for visual transmittance (T_{vis}), total solar energy transmittance (solar heat gain coefficients (SHGCs)) and the thermal transmittance (U-value) of a product are described. Shading device calculation procedures are also covered for slat-type blinds.

Some of the previous works pertaining to louvered blinds have been done for a horizontal blind sealed between the panes of an IGU. Garnet et al. (1995) carried out an experimental investigation using a guarded hot plate apparatus to determine the thermal performance of an IGU with a between-the-panes venetian blind. The centre-of-glazing U-value (U_{cog}) with shades retracted was measured to be 2.8 W/(m^2 K). They found that the effect of the venetian blinds on the U_{cog}-value of the glazing unit ranged from a 10% increase for blinds in a horizontal position ($\alpha = 0°$) to a 20% decrease with the venetian blinds in a closed position ($\alpha = 90°$). It is also concluded that from a thermal performance perspective, it is better to close the blinds hot side up, that is, the slats should point upwards on the warm side of the window with a slat angle $\alpha = 90°$.

Few measurement campaigns have been carried out. A calorimetric cell was used by Rheault and Bilgen (1990) for measuring surface temperatures of a glazing unit with integrated louvered blinds (Bilgen, 1994). Surface temperatures from measurements were compared to an analytical model. Differences in temperature prediction using the analytical model differed with approximately 7% in average and 18% at maximum. Using the analytical model, the authors found that the thermal resistance of the system was marginally changed as a function of changing slat angles of the blinds. In 2001, Breitenbach et al. (2001) presented thermal resistance measurements for a 2-pane IGU with integrated venetian blinds. The authors found that the thermal transmittance value (U-value) varied almost linearly with the slat angle from 2.92 ± 0.14 W/(m^2 K) with blinds open to 1.44 ± 0.21 W/(m^2 K) with the slats closed. This contradicts the values found by Tzempelikos (2005). During a measurement campaign performed on a double-pane window with in-between venetian blinds it was found that a blind slat angle a = –60_ gave the lowest thermal resistance and that blinds in a vertical (i.e. a = 90_) position gave the highest thermal resistance.

A study performed by Shahid and Naylor (2005) presents a numerical method for a window with internal shading. The method is validated by use of previous measurement results for tall vertical cavities, but is only addressing the centre-of-glazing properties. No validation using measurements on real windows was performed.

Huang et al. (2006) carried out measurements using a Guarded Heater Plate (GHP) apparatus, which is, in principle, similar to a guarded heat flow meter (HFM) apparatus (ISO 8301:1991, 1991). Here, centre-of-glazing U-values (U_{cog}) for double-glazing units with and without shades were measured using HFMs. This was carried out by controlling the temperature on each side of the sample using the GHP. A total of 12 sample configurations were measured. The measured values were used for benchmarking/validation of computational fluid dynamics (CFD) simulations. Values are extrapolated to also include SHGC and visual transmittance (T_{vis}) values. The main results for windows with low-emissivity (low-e) coatings and temperature difference of 20 K are shown in Table 1.

Laouadi (2009) presented an overview of existing studies related to modelling of glazing units coupled with solar shading systems. A model for calculating the properties of the centre-of-glazing area was proposed and found to correspond to measurements performed by Huang et al. (2006) within a 7% margin of error. The model was only verified for double-pane glazing units with a cavity thickness lower than 25 mm. The U_{cog}-value of IGUs with low-e coated glazings and higher cavity thicknesses (40 mm was modelled) was underestimated with the model. Furthermore, the authors pointed out that by 2006, the models regarding the

Table 1. Measured U_{cog}-values for 2-pane IGU with low-emissivity (low-e) coating on one glass pane for various blind slat angles and cavity thicknesses (Huang et al., 2006).

Slat angle (°)	U_{cog}-value (W/(m^2 K)) – cavity thickness = 18 mm	U_{cog}-value (W/(m^2 K)) – cavity thickness = 25 mm	U_{cog}-value (W/(m^2 K)) – cavity thickness = 40 mm
−75	1.87	1.65	1.78
−60	2.02	1.84	1.74
−30	2.38	1.87	1.73
0	2.65	1.94	1.76
30	2.38	1.85	1.81
60	2.00	1.68	1.82
75	1.84	1.63	1.78

IGU: insulated glazing unit.

thermal performance of shading systems are based on simple algorithms and that further validation work needs to be carried out.

None of the aforementioned publications present values for a situation with the blinds in a retracted position and only the U_{cog}-values are presented. Presenting only centre-of-glazing U-values, any effects caused by the mounting system and any motor of the venetians on the total U-value of the glazing unit are not taken into account. Such effects could be substantial as mounting systems and motors may contain relatively large amounts of continuous metal from warm to cold side, thus creating a substantial thermal bridge.

As part of the IEA SHC Annex 27 (IEA (International Energy Agency), 2005), Simmler and Binder (2008) performed measurements for the total solar energy transmittance of a glazing unit with an externally placed venetian blind. Results were compared to two numerical models, the ISO 15099:2003 (2003) model and the simplified model described in EN 13363-1:2003 (2003). They found good correlations between the numerical models and measured values. The ISO and EN standard calculation methods gave approximately 10% higher SHGC-values compared to the measured values. No measurements were performed for the thermal transmittance values (U-values) of the complete windows including frames and hardware.

Based on results from the existing literature presented here, it was found that further studies needed to be carried out due to the contradictions in the existing results. Measurements of thermal resistances for the systems described in this study have been carried out using a large-scale hot box. The results have been compared to numerical simulations.

Methodology and experimental design

Window sample and test series overview

U-values are measured for three windows: a double-, a triple- and a 4-pane window. All the windows have a venetian type of shading device of aluminium with horizontal slats mounted in the outermost glazing cavity. The windows with 2- and 3-pane glazing units are constructed with IGUs with argon gas fillings in the cavities. The shading device is remote-controlled and operated by a small aluminium encased motor mounted inside the glazing cavity, as shown in Figure 2.

The 2-pane window has a low-e coating on the exterior pane with a declared emissivity, $\varepsilon = 0.013$. The 3-pane window has a low-e coating with declared emissivities, $\varepsilon = 0.03$ and $\varepsilon = 0.013$, on the mid pane (facing the exterior cavity) and interior panes, respectively.

The window with the 4-pane glazing unit consists of a 3-pane IGU with argon fillings. An external fourth coupled glass pane is mounted on the exterior side. A manually operated (no motor) venetian blind is mounted in the exterior cavity as shown in Figure 1. The exterior, coupled pane has a hard-coat low-e coating with a declared emissivity, $\varepsilon = 0.1$. The low-e coating on the panes in the IGU has a declared emissivity, $\varepsilon = 0.013$.

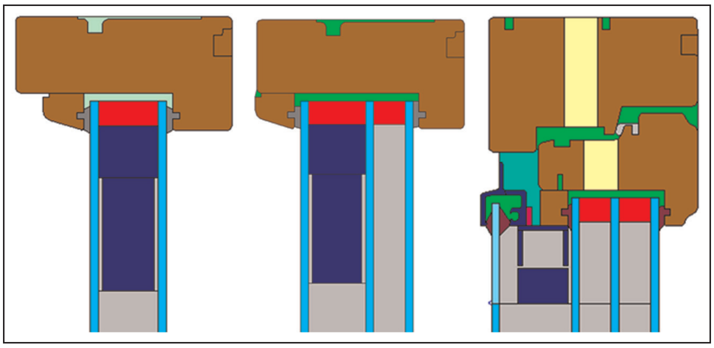

Figure 2. Graphical illustration of the 2-, 3- and 4-pane windows. Shading device, in dark blue, is shown in a retracted position. The 4-pane window (right) has a shading device integrated in a partially ventilated cavity behind an exterior coupled glass pane. The frame of the 4-pane window is insulated with polyurethane foam (shown in yellow colour). All frames are shown with the exterior side facing left.

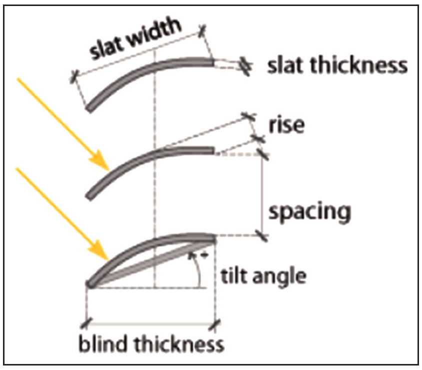

Figure 3. Slat dimensions used for simulations (LBNL, 2013). The tilt angle corresponds to the definition given in Figure 1.

The venetian blinds are made of powder-coated aluminium for all three windows. Figure 3 shows the various slat dimensions used in the calculations.

The windows with the 2- and 3-pane IGUs were not possible to dismantle, thus the slat dimensions were visually assessed. The width was assessed to be 16 mm, the rise of the slats approximately 1 mm and the spacing 12 mm. The 4-pane window slats were measured to a width of 25 mm with a rise of 1 mm and slat spacing

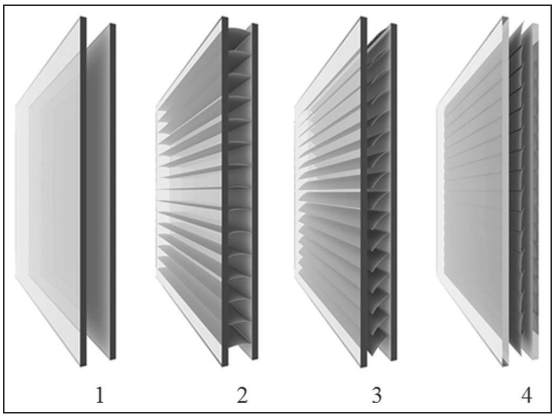

Figure 4. Illustration of shading slat angles and position configurations, as described above.

of 20 mm. The blind thicknesses for all three windows were set to 0.6 mm. This corresponds to generic data for shading slats from ISO 15099:2003 (2003). The surface properties of the blind slats have not been measured. Properties have been assumed in accordance with Table C.2 in ISO 15099:2003 (2003). For all slats, an emissivity $\varepsilon = 0.9$ has been assumed.

Each of the windows was measured in three (or four where possible) configurations, as shown in Figure 4:

1. With the blinds fully retracted.
2. With the blinds down and the slats in an open (horizontal, $\alpha = 0°$) position.
3. With the blinds down and the slats in $\alpha = 45°$ position (for the 4-pane window).
4. With the blinds down and the slats in a closed (vertical, $\alpha = 90°$) position.

Table 2 shows an overview and description of the window configurations that have been measured. Measurement series numerations are shown in the rightmost column of the table. The shading slats in the 2- and 3-pane windows could only be adjusted to vertical and horizontal positions due to limitations of the shading device control unit.

The hot-box test facility – test procedure and instrumentation

Measurements have been carried out in a guarded hot-box apparatus according to procedures described in ISO 8990:1994 (1994) *Determination of steady-state*

Table 2. Test sample overview and description.

Window description	Test series no. and corresponding blind configuration

2-pane glazing unit
• Window size 1230 × 1480 mm ($w \times h$)
• Fixed-frame window
• IGU construction: 4-29Ar-E4, 90% argon
• Venetian blind, aluminium slats, in cavity
  ○ Slat width 16 mm
  ○ Slat thickness 0.6 mm
  ○ Slat rise 1 mm
  ○ Slat spacing 12 mm
  ○ Slat emissivity, $\varepsilon = 0.9$
• Wooden frame
  ○ Frame width 55 mm
  ○ Frame depth 105 mm
	Blind position
	1. Retracted
	2. Deployed, horizontal slats, $\alpha = 0°$
	3. Deployed, vertical slats, $\alpha = 90°$

3-pane glazing unit
• Window size 1230 × 1480 mm ($w \times h$)
• Fixed-frame window
• IGU construction: 4-29Ar-4E-16Ar-E4, 90% argon
• Venetian blind, aluminium slats, in outermost cavity
  ○ Slat width 16 mm
  ○ Slat thickness 0.6 mm
  ○ Slat rise 1 mm
  ○ Slat spacing 12 mm
  ○ Slat emissivity, $\varepsilon = 0.9$
• Wooden frame
  ○ Frame width 55 mm
  ○ Frame depth 105 mm
	Blind position
	4. Retracted
	5. Deployed, horizontal slats, $\alpha = 0°$
	6. Deployed, vertical slats, $\alpha = 90°$

4-pane glazing unit
• Window size: 1200 × 1200 mm ($w \times h$)
• Operable window
• 3-pane IGU + 1 exterior coupled pane
• IGU construction: 4-24-4E-16Ar-4-16Ar-E4, 90% argon
• Venetian blind, aluminium slats, in outermost (coupled) cavity
  ○ Slat width 25 mm
  ○ Slat thickness 0.6 mm
  ○ Slat rise 1 mm
  ○ Slat spacing 20 mm
  ○ Slat emissivity, $\varepsilon = 0.9$
• Wood frame insulated with 17 mm polyurethane foam
  ○ Sill width 101 mm
  ○ Jamb width 94 mm
  ○ Head width 105 mm
  ○ Frame depth (all parts) 105 mm
	Blind position
	7. Retracted
	8. Deployed, horizontal slats, $\alpha = 0°$
	9. Deployed slats, $\alpha = 45°$
	10. Deployed, vertical slats, $\alpha = 90°$

IGU: insulated glazing unit.
The right column shows the hot-box measurement series numeration corresponding to test sample series numbers discussed in section 'Results'.

Figure 5. The large-scale guarded hot-box test facility used for the measurements.

thermal transmission properties – calibrated and guarded hot box and ISO 12567-1:2010 (2010) *Thermal performance of windows and doors – determination of thermal transmittance by the hot-box method – part 1: complete windows and doors*. The hot box used is shown in Figure 5.

The tests are performed at steady-state conditions: + 20°C on the warm side and 0°C on the cold side. Window U-values are based on the measured heat flows, surrounding temperatures and window area. The U-value given is the mean value of 24 1-h-long measurement periods.

The windows are mounted in a template constructed as a sandwich element consisting of a 100-mm-thick Extruded Polystyrene (XPS) core, clad with 12 mm plywood on the faces exposed to the hot and cold sides. The joints between the window and the surrounding panel are sealed with tape on both sides to ensure an airtight seal. Minor gaps between window frame and template were filled with expanded polystyrene (EPS) with approximately the same thermal conductivity as the XPS used in the template.

The metering area of the hot box is 2.45 m × 2.45 m. The window is placed in the middle of the metering area template wall at a distance of 1.0 m from the floor to the lower edge of the frame.

Surface thermal resistance coefficients were adjusted close to the standardized ones prior to the tests by adjusting air-flow velocities adjacent to the template surface on the cold side. Natural convection-driven air-flow was maintained on the warm side. This gives a thermal resistance coefficient very close to the standard value. However, during the measurements, the surface thermal resistances may differ slightly from the standardized values. Corrections to the values are made for these deviations, so that all U-values are stated with normalized surface thermal resistance coefficients as specified in ISO 8994:1994 (1994). The standardized conditions are interior surface thermal resistance $R_{si} = 0.13\,W/(m^2\,K)$ and external surface resistance $R_{se} = 0.04\,W/(m^2\,K)$.

Instrumentation – HFMs. Centre-of-glazing U-values (U_{cog}) were measured using two polyurethane (PU) 43 T HFMs, from Hukseflux (2013), with a declared accuracy of ±5% at 20°C. These were mounted mid-height 10 cm to the sides of the vertical symmetry axis of the IGUs on the warm side of the samples. Surface temperatures were measured adjacent to the HFMs.

Low-e coatings and gas fillings in window cavities. In order to confirm the amount of argon in the cavities, the argon concentrations were measured using an Argon Detection Kit, *Gasglass 1002* from Vetromac. Due to limitations in the instrument, gas concentrations could only be measured where the glass pane of the cavity facing the environment does not have a low-e coating. This led to the condition that only the cavity of the 2- and 3-pane IGUs could be measured. These were measured to have an argon gas concentration of 90%.

Uncertainty assessments of hot-box measurements

The uncertainties associated with the hot-box measurements have been assessed in accordance with the procedure described in ISO 12567-1:2010 (2010). The total uncertainty propagation of the measured U-value $\Delta^P U_w/U_w$ has been derived using the root-mean-square (RMS) method as shown in equation (1)

$$\frac{\Delta^P U_w}{U_w} = \sqrt{\left[\frac{\Delta^P \Phi_w}{\Phi_w}\right]^2 + \left[\frac{\Delta^P A_w}{A_w}\right]^2 + \left[\frac{\Delta^P \delta\theta_{ie}}{\theta_{ie}}\right]^2} \quad (1)$$

where $\Delta^P \Phi_w/\Phi_w$ is the uncertainty in sample heat flow (W), $\Delta^P A_w/A_w$ is the uncertainty of projected area of sample (m^2) and $\Delta^P \delta\theta_{ie}/\delta\theta_{ie}$ is the uncertainty in temperature difference between warm and cold sides (K).

The uncertainty in the sample heat flow is based on the heat balance equation for the metering chamber. The uncertainties in test sample specimen heat flow, $\Delta^P \Phi_w/\Phi_w$, are expressed using equation (2)

$$\frac{\Delta^P \Phi_w}{\Phi_w} = \sqrt{\left[\frac{\Delta^P \Phi_{IN}}{\Phi_w}\right]^2 + \left[\frac{\Delta^P \Phi_{sur}}{\Phi_w}\right]^2 + \left[\frac{\Delta^P \Phi_{EXTR}}{\Phi_w}\right]^2 + \left[\frac{\Delta^P \Phi_{FL,w}}{\Phi_w}\right]^2} \quad (2)$$

Table 3. Properties of materials used in the simulations.

Window	Component	Material	Conductivity (W/(m^2 K))	Emissivity (–)
2-, 3- and 4-pane windows	Shading slats	Powder-coated aluminium	160	0.9
	Frame	Wood	0.12	0.9
	Cavities	NFRC-model (LBNL, 2013)	NA	0.9
	Spacer	Equivalent model	0.45	0.9
2- and 3-pane	Sealing gaskets	Butyl rubber	0.24	0.9
4-pane	Sealing gasket type I	EPDM	0.19	0.9
4-pane	Sealing gasket type II	CellP	0.08	0.9
4-pane	Sealing gasket type III	Qlon	0.03	0.9
4-pane	Exterior cladding	Aluminium (painted)	160	0.9
4-pane	Insulation layer	Polyurethane foam (PUR)	0.023	0.9

NFRC: National Fenestration Rating Council; LBNL: Lawrence Berkeley National Laboratory; EPDM: ethylene propylene diene monomer.

where $\Delta^P\Phi_{IN}$ is the uncertainty in power input to metering chamber (W), $\Delta^P\Phi_{sur}$ is the uncertainty in surrounding panel heat flow (W), $\Delta^P\Phi_{EXTR}$ is the uncertainty in metering chamber wall heat flows (W) and $\Delta^P\Phi_{FL,w}$ is the uncertainty in test sample flanking heat loss (W).

No correlation between the various terms of the balance equation has been found. A calibration experiment for the thermocouples was carried out using a reference temperature bath. The relative scattering in measured temperatures between the thermocouples was found to be lower than 0.02°C. Thus, it can be concluded that the influence from the factor $\Delta^P\delta\theta_{ie}$ as described in equation (1) is negligible. The areas of the windows ($\Delta^P A_w$) are measured with an accuracy of $\pm$0.5 mm and can thus be concluded to be negligible compared to the uncertainty of the $\Delta^P\Phi_w/\Phi_w$ term in equation (1).

The uncertainties stated in this work are given with a coverage factor of 2 standard deviations and the corresponding 95% confidence interval.

Numerical simulations

U-values for the glazing units and frames have been calculated using the WINDOW 7.0 and THERM 7.0 simulation tools, respectively (LBNL, 2014). Glazing unit U-values have been calculated according to ISO 15099:2003 (2003). Frame- and whole window U-values were calculated using the linear thermal transmittance method for edge-of-glass effects according to the definitions given in ISO 10077-1:2006 (2008) *Thermal performance of windows, doors and shutters – calculation of thermal transmittance – part 1: general*. Table 3 shows the material properties used in the simulations for all windows. Spacers were modelled as a single

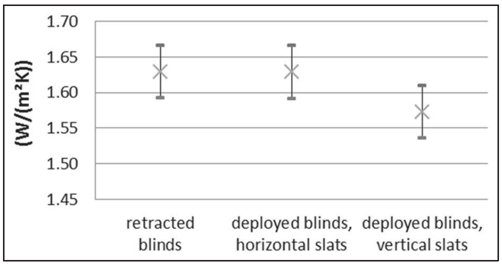

Figure 6. Measured U_{window}-values for the 2-pane window. The horizontal bars show the measurement uncertainties within the 95% confidence interval.

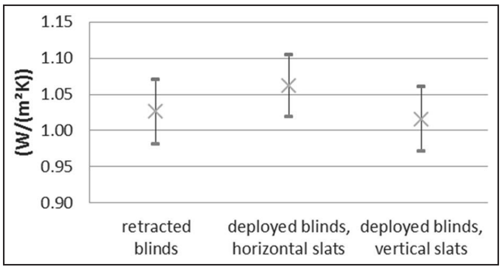

Figure 7. Measured U_{window}-values for the 3-pane window. The horizontal lines show the measurement uncertainties within the 95% confidence interval.

(homogeneous) component with an equivalent conductivity $\lambda = 0.45\,W/(m\ K)$. Standardized boundary conditions were 20°C interior temperature and 0°C exterior temperature. Surface thermal resistances of the interior and exterior surfaces of the IGUs were set to 0.04 and 0.13 $(m^2\ K)/W$, respectively. Boundary conditions were chosen according to simplified rules given in ISO 10077-1:2006 (2008).

To further study the effect of the shading device on the total U_{window}-value of the windows, all three windows were modelled with and without the shading.

Results

Measurement results

Figures 6 to 8 show the measured U-values, U_{window}, for the 2-, 3- and 4-pane windows. Table 4 shows the measured U_{window}-values alongside the measured centre-of-glazing U-values, U_{cog}.

Table 4. Test series description and the corresponding measured U-values for the whole window, U_{window}, and the centre-of-glazing U-value, U_{cog}.

Test series ID	Test series description	Slat angle, α (deg)	U_{window} (W/(m^2 K))	dU_{window} (%)	U_{cog} (W/(m^2 K))	dU_{cog} (%)
1	2-pane glazing with retracted (open) blinds	–	1.63 ± 0.04	–	1.33 ± 0.07	–
2	2-pane glazing with deployed blinds, horizontal slats	0	1.63 ± 0.04	0	1.48 ± 0.07	11
3	2-pane glazing with deployed blinds vertical slats	90	1.57 ± 0.04	−4	1.25 ± 0.06	−6
4	3-pane glazing with retracted (open) blinds	–	1.03 ± 0.04	–	0.87 ± 0.04	–
5	3-pane glazing with deployed blinds, horizontal slats	0	1.06 ± 0.04	3	0.92 ± 0.05	6
6	3-pane glazing with deployed blinds vertical slats	90	1.02 ± 0.04	−1	0.81 ± 0.04	−7
7	4-pane glazing with retracted (open) blinds	–	0.84 ± 0.04	–	0.61 ± 0.03	–
8	4-pane glazing with deployed horizontal blinds (closed blinds with horizontal slats)	0	0.85 ± 0.04	1	0.60 ± 0.03	−2
9	4-pane glazing with deployed blinds, slats in 45° position	45	0.83 ± 0.04	−1	0.58 ± 0.03	−5
10	4-pane glazing with deployed blinds vertical slats	90	0.81 ± 0.04	−4	0.57 ± 0.03	−7

The columns dU_{window} and dU_{cog} show the change in measured U-value in percent compared to the retracted shade configuration case for each window.

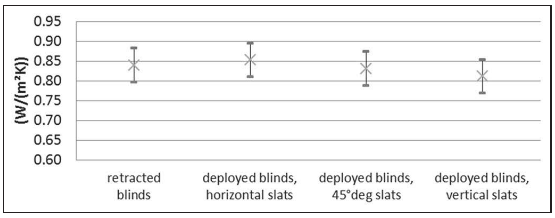

Figure 8. Measured U_{window}-values for the 4-pane window. Upper and lower uncertainty values shown with horizontal lines.

2-pane window results. From Figure 6, it can be seen that closing or opening the blinds has little effect on the U-value of the window. Deploying the blinds, keeping the slats in a horizontal position does not affect the U_{window}-value. When shutting the blinds (vertical slats, $\alpha = 90°$), one can observe a reduction in the measured mean U_{window}-value of approximately 4% compared to the retracted blinds configuration.

The uncertainty boundaries calculated using equation (1) are shown as horizontal bars over and below the mean value in Figure 6.

3-pane window results. From Figure 7, it can be observed that the 3-pane window shows a slightly different behaviour than the 2-pane window. A 3% increase in the U_{window}-value was found when the blinds were deployed with the slats in a horizontal position (slat angle, $\alpha = 0°$) compared to the retracted blinds configuration. The reduction of the measured mean U_{window}-value when turning the slats into a vertical position ($\alpha = 90°$) was less than 1%.

4-pane window results. From Figure 8, one can see that operating the blinds in the 4-pane window has minor effect on the measured mean U_{window}-value. Compared to the retracted blinds configuration, deploying the blinds with horizontal slats (slat angle, $\alpha = 0°$) increases the U_{window}-value with approximately 1%, whereas turning the slats shut ($\alpha = 90°$) will give a 4% decrease in U_{window}-value.

Measurement results – summary and centre-of-glazing U-values. The measured U-values for the whole window, U_{window}, and the centre-of-glazing U-values, U_{cog}, are shown in Table 4 and Figure 9. The U_{cog}-values were measured using HFMs.

For the 2-pane window, it was found that deploying the blinds gave an increase in U_{cog} of 11%. However, when tilting the slats from a horizontal ($\alpha = 0°$) to a vertical position ($\alpha = 90°$), a decrease in U_{cog} of 11% was found.

Numerical simulation results

Table 5 and Figure 10 show the measured mean U-values of the three windows alongside the numerically simulated values found using the WINDOW simulation tool for U_{cog}-values and THERM for the frame and edge-loss values.

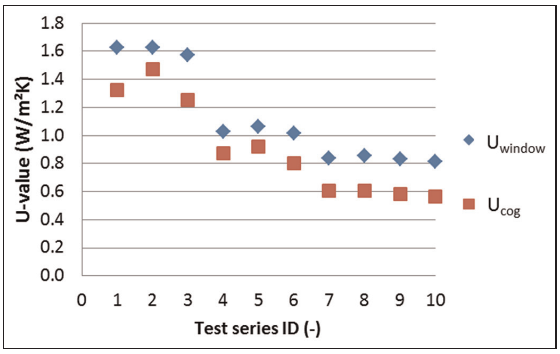

Figure 9. Comparison of measured mean values of whole window, U_{window}, and centre of glazing U-values, U_{cog}.

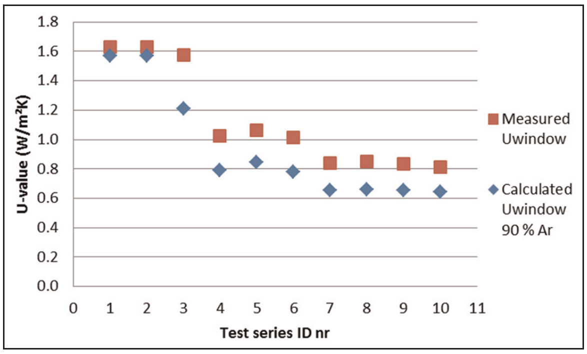

Figure 10. Comparison of measured and calculated mean U-values of whole windows, U_{window}.

Table 5 and Figure 10 show that there are some discrepancies between measured and calculated values. The 2-pane window has good correspondence between measured and simulated values when the shading is either retracted or deployed with horizontal ($\alpha = 0°$) slats. The closed blind vertical slat position, however, shows discrepancies of 27% in the initial simulation case where slats were modelled as completely shut using WINDOW. Manual inspection after the measurement showed that there were openings between the shading slats when the slats were set in a closed (vertical slats) position. This was corrected for by adjusting the slat angle to 80° in the simulations. A 5% increase in U-value was found when slat angles

Table 5. Test series description and the corresponding measured and calculated U-values for the whole window, U_{window}, and the centre-of-glazing U-value, U_{cog}.

Test series ID	Test series description	Measured U_{window} ($W/(m^2 K)$)	Calculated U_{window} ($W/(m^2 K)$)	Measured U_{cog} ($W/(m^2 K)$)	Calculated U_{cog} ($W/(m^2 K)$)
1	2-pane glazing with retracted (open) blinds	1.63 ± 0.04	1.57	1.33 ± 0.07	1.24
2	2-pane glazing with deployed horizontal blinds (closed blinds with horizontal slats)	1.63 ± 0.04	1.57	1.48 ± 0.07	1.38
3	2-pane glazing with deployed vertical blinds (closed blinds with vertical slats)	1.57 ± 0.04	1.19	1.25 ± 0.06	0.90
4	3-pane glazing with retracted (open) blinds	1.03 ± 0.04	0.79	0.87 ± 0.04	0.58
5	3-pane glazing with deployed horizontal blinds (closed blinds with horizontal slats)	1.06 ± 0.04	0.85	0.92 ± 0.05	0.66
6	3-pane glazing with deployed vertical blinds (closed blinds with vertical slats)	1.02 ± 0.04	0.78	0.81 ± 0.04	0.52
7	4-pane glazing with retracted (open) blinds	0.84 ± 0.04	0.65	0.61 ± 0.03	0.52
8	4-pane glazing with deployed horizontal blinds (closed blinds with horizontal slats)	0.85 ± 0.04	0.66	0.60 ± 0.03	0.53
9	4-pane glazing with blinds in 45° position (closed blinds with slats in 45° angle)	0.83 ± 0.04	0.65	0.58 ± 0.03	0.51
10	4-pane glazing with deployed vertical blinds (closed blinds with vertical slats)	0.81 ± 0.04	0.64	0.57 ± 0.03	0.50

were adjusted from fully closed (90°) to 80°. However, the simulated U-values are still 25% lower than the measured values even after adjusting the slat angle to 80° in the WINDOW model.

For the 3-pane window, a more systematic difference between measured and simulated values was found. Hence, the amounts of argon gas in the cavities were measured. For both the 2- and 3-pane IGUs, the amounts of argon in the cavities were found to be in accordance with the producers' specification of 90%.

The remaining calculation results for the 3- and 4-pane glazing units were consistently underestimated with approximately 20% compared to measured values. The effect of removing the shading devices from the windows was calculated using the numerical models. The results showed that a considerable thermal bridging effect was caused by the protruding aluminium of both the shading slats and the other hardware of the devices. For the 2-pane window, a 12% reduction (improvement) of the U_{window}-value was found when removing the shading device from the cavity. A 6% reduction was found for the 3-pane window, and a 2% reduction was found for the 4-pane window.

Matching of measured and modelled values of U_{cog}

Since relatively large differences were found between measured and modelled U-values for most of the cases, additional calculations have been carried out in order to investigate how the quality of the low-e coatings influences the centre-of-glazing U-values. The glazed area is a substantial part of a window product, thus it has a dominating role in the total thermal transmittance of the fenestration product (U_{window}).

The focus of the verification is on the centre-of-glazing performance. Glazing thermal transmittance is not a primary property measured in hot-box apparatus; however, defined and constant boundary conditions allow us to estimate centre-of-glazing thermal performance using heat flux meters. In this study, two identical heat flux meters were installed in the centre area of the glazing which is not influenced by glazing edges, as described in section 'Instrumentation – HFMs'. Sets of thermocouples were used to record temperature on the outside and inside surfaces of the glazing units adjacent to the HFMs. A parametric study was conducted in order to investigate the difference between modelled and measured values of U-values and temperature differences. The actual physical dimensions of the glazing units were used in the model.

First, the model was run with declared values for the windows, that is, low-e coatings as declared by the manufacturer and 90% argon gas fill concentrations. Gas concentrations of the 2- and 3-pane IGUs and position of low-e coatings were checked according to the description in section 'Low-e coatings and gas fillings in window cavities'. The remaining key property which has an important influence on thermal properties of the window is the value of emissivity of the low-e coatings of the glazing surfaces.

Simulations were carried out in order to match the emissivity which will give a good approximation to the measured U_{cog}-values. After U-values were matched, temperature differences were checked. Modelled temperature differences after U-value matching are relatively close to the measured values for all windows, as shown in Table 6. This could suggest that the declared values of the low-e coatings might be incorrect. The U_{cog}-values in Table 5 show the difference between the measured and modelled values.

Discussion

Looking at the measured results for the U-values of the whole windows (U_{window}) and the centre of glazing U-values (U_{cog}), it is clear that the effect of operating the venetian blinds is minor. For the 2-pane window, a reduction in U_{window}-value of approximately 4% was found for the deployed blinds with vertical slats, compared to the retracted blinds configuration. For the 3-pane window, a U_{window} reduction of 1% was found, and for the 4-pane window, a maximum reduction of 4% was found. For the cases with deployed blinds in a horizontal position ($\alpha = 0°$), no change in U_{window}-value was found for the 2-pane window, a 3% increase was found for the 3-pane window and a 1% increase was found for the 4-pane window.

An approximate 6%–7% maximum reduction in centre-of-glazing U_{cog}-value was found for all three windows when blinds were deployed with vertical ($\alpha = 90°$) slats. The changes in U_{cog}-values as a function of blind configurations are smaller than expected when looking at the previous studies by Huang et al. (2006) and Garnet et al. (1995), where a reduction of the U_{cog}-value of 18% was found for a 2-pane window with a 25 mm gap between the glass panes by Huang et al. (2006). Similarly, Garnet et al. (1995) found a 20% reduction in U_{cog} when deploying the blinds with a slat angle $\alpha = 90°$ compared to a retracted blinds configuration. However, the results carried out in this work follow the same trends as both Huang and Garnet. Furthermore, both Huang's and Garnet's measurements were performed for the centre-of-glazing area, and they were carried out with the window in a horizontal position, and thus, it could be expected that heat transfer due to convection in the cavity might be reduced to a larger degree than for a vertical oriented cavity, thus contributing to a larger potential effect on the U_{cog}-value.

If one compares the measured centre-of-glazing U-values (U_{cog}) with the U_{window}-values, a slightly different behaviour can be found. The differences are most pronounced for the 2-pane window. Here, the U_{cog}-value increases by 11%, whereas the U_{window}-value is unaltered when the blinds are deployed ($\alpha = 0°$) compared to the retracted blinds configuration. This deviation can, however, most likely be attributed to the fact that the blinds are causing a large thermal bridge even when retracted. The difference in U_{cog} will thus be counteracted by the thermal bridge caused by the aluminium of the retracted slats. Hence, these results indicate that the total amount of aluminium protruding from cold to warm side is the determining factor on the U_{window}-value for a window with a 2-pane IGU.

Table 6. Measured and modelled centre-of-glazing U-values for 2-, 3- and 4-pane glazing units with retracted shading devices.

Window	Measured values		Modelled with declared values				Modelled with adjusted emissivity			
	U_{cog} (W/(m^2 K))	dT (K)	ε (–)	U_{cog} (W/(m^2 K))	dU_{cog} (%)	dT (K)	ε (–)	U_{cog} (W/(m^2 K))	dU_{cog} (%)	dT (K)
2-pane	1.33	15.8	0.013	1.24	7	15.7	0.037	1.33	0	15.5
3-pane	0.87	16.8	0.03/0.13	0.58	33	18.0	0.173/0.173	0.87	0	17.0
4-pane	0.61	17.6	0.1/0.013	0.52	15	18.3	0.173/0.173	0.63	−3	17.9

Adjustments to the model have been made to match U-values and temperature differences across the glazing units. The second column with modelled values shows values where emissivity of low-emissivity (low-e) coatings has been adjusted.

A similar trend was found in the numerical simulation results. However, when the blinds are deployed with a slat angle $\alpha = 90°$, large differences were found between the simulated and measured values of the 2-pane window. The difference is smaller for the 3-pane window and even smaller for the 4-pane window. The discrepancies are likely caused by an underestimation in the numerical model due to the modelling assumptions. In the model, it is assumed that the venetian blinds are airtight towards the glazing edges in the top, bottom and side edges of the IGU. Thus, convection effects occurring here are unaccounted for in the numerical model. This will lead to a lower calculated U-value than what is found through measurements where such convection effects are likely to occur. Such convection effects will be smaller in a 3- and 4-pane glazing unit, due to a smaller temperature gradient across the cavity with the shading device, thus reducing the differences due to the underestimation of the convection in the numerical model. This is confirmed by the diminishing differences between measurements and calculations as a function of increasing number of panes in the glazing units.

Here, the U_{cog}-values were found to increase by approximately 11% when the blinds were deployed with a slat angle $\alpha = 0°$. This is as expected, as the operation of the blinds is mainly related to the effect on the centre-of-glazing U-value.

The effect of removing the shading devices from the windows in the numerical models showed that a considerable thermal bridging effect was caused by the protruding aluminium of both the shading slats and the other hardware of the devices. For the 2-pane window, a 12% reduction (improvement) of the U_{window}-value was found when removing the shading device from the cavity. A 6% reduction was found for the 3-pane window, and a 2% reduction was found for the 4-pane window.

Conclusion

Measurements have been carried out in order to investigate U-values of windows with 2-, 3- and 4-pane glazing units with integrated (in-between pane) venetian-style shading units. The aim of the study has been to assess the effect of operating the blinds on the U-value of the windows. The U-value as a function of various slat angles and blind positions has been studied. The measurements have been compared to numerical studies performed using the THERM/WINDOW simulation tools.

The measured mean U-values for the windows with closed blinds with horizontal slats are unaffected for the window with the 2-pane IGU. The U-value of the 3-pane IGU window is increased by 3% compared to retracted (open) blinds, whereas the U-value of the window with the 4-pane glazing unit is increased by 1%.

The measured mean U-values for the windows when closing the blinds with vertical slats are reduced by approximately 3% for the windows with the 2- and 4-pane glazing units compared to retracted (open) blinds. The mean U-value of the window with the 3-pane glazing unit is reduced by 1%.

Shading systems like this are, by some, considered to be an effective system for reducing U-values of the glazing units when they are closed. Based on the measurements carried out in this work, it can be concluded that shading devices with properties like the ones measured should not be considered as an effective system for reducing U-values of windows.

Similar trends as for the measured values were found in the calculated values. With the exception of the window with the 2-pane IGU, minor reductions in the U-values of the windows were found when closing the blinds shut.

Simulations showed that the instalment of a shading device in the gas-filled cavities of the 2- and 3-pane IGUs will increase the U-value of the glazing units. The protruding aluminium components of the shading device motor as well as the venetian blinds themselves act as thermal bridges. For the 2-pane IGU, the U-value of the window was found to decrease by approximately 12% from 1.57 to 1.42 W/(m^2 K) if the shading device was removed. Thus, any beneficial effects expected to be achieved by using the venetians as an additional layer in the IGU were found to be counteracted by the thermal bridging. The U-value of the window is less affected when removing the shading device motor and the shading blinds themselves for the windows with 3- and 4-pane glazings. A U-value reduction of 6% from 0.79 to 0.75 W/(m^2 K) was found for the window with a 3-pane IGU. The U-value of the window with the 4-pane glazing unit is reduced by only 2%, from 0.654 to 0.647 W/(m^2 K).

The numerically calculated values were in general found to be lower than the measured values. The reasons for this can be many. The actual low-e coatings can be of an inferior quality than what the declared values are stated as. Second, even though the pressure difference over the windows (i.e. pressure difference between the warm and cold chamber of the hot box) was found to be close to zero at the start and end of the measurement periods, some air leakages could have occurred during the measurement periods. This will contribute to a higher heat flow from warm to cold side. This increase in heat flow is contributed to a higher U-value of the window. Thermal bridging effects, other than the ones discussed in relation to the shading devices, could also be a contributing factor for the modelled values being lower than the measured U-values.

Improvement possibilities of shading systems

The solar shading device positioned in the outermost cavity in the three measured windows does not have large effects related to improving the U-value of the windows. On the contrary, simulations showed that the introduction of the shading device will have a negative effect on the U-value of the windows compared to ones without the shading device. The protruding aluminium components of the shading device motor as well as the venetian blinds themselves act as thermal bridges.

In order to achieve more effective shading devices, several factors should be explored:

- Redesigning motors in order to minimize protruding aluminium from cold to warm side.
- Reducing slat thermal conductivity in order to reduce thermal bridging effects.
- Improving the surface properties of slats (i.e. reduce emissivity) in order to reduce radiative heat loss from warm to cold side.
- Improving the airtightness of the shading layer by reducing openings between slats when in a closed position and by making tight connections towards the edges of the cavity.

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Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

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Scientific paper VI

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Multilayer Glazing Technologies: Key Performance Parameters and Future Perspectives

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Multilayer Glazing Technologies:
Key Performance Parameters and Future Perspectives

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Keywords: Glazing, multilayer, window, U-value, solar heat gain coefficient, SHGC, g-value, solar factor

ABSTRACT

Buildings account for a significant part of the total manmade greenhouse gas emissions and energy use. Reducing CO_2 emissions and energy consumption in the building sector are key issues. Optimizing the building envelope and its components is one of the main factors for reducing the energy demand of buildings.

Previous studies show that a large part of the net energy demands of an office building is related to window heat loss and cooling demands induced by solar irradiance. Windows with improved thermal transmittance (U-value) and solar heat gain coefficient (SHGC or g-value) are important for reducing the related energy demands. Windows must, however, provide daylight to the interior, implying that the visible transmittance of such glazing units must be kept at a required and satisfactory level. High visible transmittance values are traditionally difficult to achieve in conjunction with very low thermal transmittance values. Increasing the number of layers in the glazing unit of a window is an effective way of improving (i.e. reducing) the thermal transmittance value of the window.

In this study, simulations with the aim of identifying the parameters that play a key role in improving thermal performance of multilayer glazing units have been carried out. An overview of interesting new products and application cases is also given.

It has been found that increasing the number of glass panes in the insulating glazing units (IGU) yields U-value reductions that decrease for each added glass pane. Furthermore, improving the low-emissivity surface coatings of panes in an IGU yields little possibility for improvement compared with today's state-of-the-art technologies. Cavity thicknesses between 8 and 16 mm were found to be optimal for IGUs with four or more panes. Reducing the gas thermal conductivity was found to have the largest impact on the U-value. The effect, however, gets less pronounced with an increased number of panes in the IGUs. Improving the low-emissivity surface coatings beyond the best-available technology has a minor effect in U-value reductions.

In addition to the thermal performance of the glazing units, optical properties, aesthetics, ageing properties and robustness should be further studied before the use of such multilayer IGUs may be recommended. Preliminary numerical simulations have demonstrated that thermal stresses to the glazing units due to high cavity temperatures can pose a problem for the robustness and lifetime of such units.

1 INTRODUCTION

Buildings account for a significant part of the total manmade greenhouse gas emissions and energy use. Increasing demand for CO_2 emission reductions makes a decrease of the built environment's energy demand vital to achieving these goals. Optimizing the building envelope and its components is one of the key factors for reducing the energy demand of buildings.

Windows are key elements in buildings that have an explicit goal of reducing energy demands both in operation and material use. Previous studies show that a large part of the net energy demands of an office building is related to window heat loss and cooling demands induced by solar irradiance [1, 2].

There is a scarcity of published scientific work related to the topic of *multilayer window technologies*. Multilayer in this context is defined as glazing units with four or more layers made of glass or other transparent materials. Hence, in this study, a state-of-the-art review is presented, alongside an overview of promising new products, applications and future perspectives and improvement possibilities for multilayer glazing technologies.

One disadvantage of insulating glazing units (IGU) with four or more layers is the increased weight of the IGU. Adding more layers increases the weight, creates difficulties with transport and mounting, and operating the windows once in place may become impractical and cumbersome. In order to maintain the favourable thermal and optical properties while keeping the weight of the IGUs at an acceptable low level, a solution would be to use non-structural intermediate layers in the IGU. The outer panes can be kept as thick as needed for maintaining the function of structural integrity, safety, soundproofing, fire resistance, etc. while the thickness of the intermediate layers can be reduced since they do not need to have any structural integrity other than being self-supportive. Applications using polymer-based foils and thin glass layers have been found in the literature. Practical examples of such glazing units will be further discussed within this study. An alternative to the thin film or thin glass technologies is the application of lightweight glass materials. Although interesting, the development of such new glass materials is novel and in its infant stage. Tao et.al [3, 4] have been exploring the possibility of incorporating aerogel granules in float glass in order to reduce the weight of glass panes. The authors found that the weight of a glass pane could be reduced by almost 30 % to approximately 1.6 - 1.8 g/cm³, compared to normal float glass with density 2.5 g/cm³, while at the same time maintaining a high visible transmittance of approximately 95 % at 500 nm.

Using suspended foil is a promising window technology that is starting to permeate the market. Here, intermittent glazing layers in an IGU are replaced with several thin, polymer films. This contributes to a substantial weight reduction of the glazing units compared to their all-glazed counterparts, hence leading to the possibility of producing reasonably lightweight, highly insulating units. The suspended foil technology is not very common among the normal insulated glazing units but their very good thermal insulating properties could make them especially suitable for cold climates.

Window glazing and the various related aspects are addressed in several studies. In two recent review article of fenestration products, Jelle et al. [5] and Cuce and Riffat [6] present, among other topics, current and future glazing technologies. Multilayer glazing units using conventional float glass, suspended film technologies and ultra-thin glass technologies for future applications in glazing units are also discussed, e.g. fenestration technologies of both today and tomorrow [5]. Cuce and Reffats [6] main finding regarding this topic is that the solar transmittance in multilayer glazing units are largely governed by the surface properties of the glass panes and that the effect of the glass thicknesses are negligible. Solar radiation glazing factors including electrochromic windows are studied in [7], miscellaneous energy aspects of windows and window frames in [2, 8, 9], and a state-of-the-art review and future perspectives on window spacers and edge seals in insulating glass units in [10].

Work carried out at Lawrence Berkeley National Laboratories (LBNL) [11] includes studies of window prototypes utilizing a suspended foil in-between structural glass layers. Arasteh et al. [11] report that a three-pane glazing unit using non-structural suspended layers in-between the outer glass panes yields glazing units with the same thermal performance as traditional three-pane IGUs but with a substantial weight reduction.

The focus of the optimization study carried out in this work is that of improving the thermal and optical properties of the windows in order to reduce the energy demand for buildings. Furthermore, it is obvious that reducing the amount of glass in the windows by reducing glazing layer thicknesses will reduce the need for raw materials and thus improve the carbon footprint of the window. A further elaboration of this is, however, not within the scope of this work.

The scope of this study relates to glass technologies and performance. The total performance of a window is made up of three main components: the glazing unit, the frame and the spacer. With respect to frame and spacer technologies, suggested reading can be found in various studies in the literature [9, 10, 12]. For energy aspects of the windows of tomorrow, refer to the work by Grynning et al. [2], Thalfeldt et.al [13] and Manz and Menti [14].

2 GLAZING UNITS – KEY PROPERTIES

The following discussion is related to the centre-of-glazing thermal performance of an IGU. Edge-of-glass losses due to the spacers and window frame effects are not included in this work. The reader may find more information in the work carried out by Gustavsen et al. [9, 12].

2.1 Thermal properties

2.1.1 General

The total heat transfer in a glazing unit is the sum of gas convection, conduction and radiation as well as the solid-state conduction in the glass panes. One or more of these heat transfer mechanisms can be reduced in order to improve the thermal performance of the IGU.

Float glass is a good heat conductor, with a typical heat conductivity of $\lambda \approx 1$ W/(mK). Consequently, the bulk of the heat resistance of an IGU is made up of the surface heat transfer coefficients and the thermal resistance of the cavities in the IGU. It is primarily the heat resistance of the cavities that can be increased in order to lower the thermal transmittance (U_{cog}-value) of the IGU. The U-value is the inverse value of the total heat resistance of the centre-of-glazing, as shown in Eq. 1.

$$U_{cog} = (R_{cog})^{-1} = \left(\sum_{i=1}^{n} R_{gp} + \sum_{i=1-1}^{n} R_{cavity,i} + R_{si} + R_{se}\right)^{-1} \quad (1)$$

Where:

U_{cog}	=	Centre-of-glazing thermal transmittance	(W/(m²K))
R_{cog}	=	Centre-of-glazing thermal resistance	(m²K/W)
R_{gp}	=	Centre-of-glazing thermal resistance from glass panes	(m²K/W)
R_{cog}	=	Centre-of-glazing thermal resistance from cavities	(m²K/W)
R_{cavity}	=	Centre-of-glazing thermal resistance from cavity *i*	(m²K/W)
R_{si}	=	Warm side surface heat transfer coefficient	(m²K/W)
R_{se}	=	Cold side surface heat transfer coefficient	(m²K/W)

The thermal resistance of a single cavity, R_{cavity}, is affected by the sum of the three heat transfer mechanisms: gas conduction, convection and radiation.

2.1.2 Gas conduction

The gas conduction is governed by the thermal conductivity and thickness of the gas layer in the cavities. The thermal resistance can be improved by increasing the cavity thickness or by reducing the thermal conductivity of the gas filling. Inert gases like argon, krypton and xenon are typical examples of gases with lower conductivity values than air. Argon is the most commonly used gas as both krypton and xenon are rather expensive and not so readily available. Introducing vacuum in the cavities will more or less cancel gas conduction (as well as convection), but this introduces other challenges, as discussed by Jelle et al. [5]. The solid-state heat conduction of the glass panes of the glazing unit is governed by the conductivity of the glass or other material used in the panes. The thickness of the glass panes, however, is limited and minor thermal resistance can be contributed to the glass panes compared to the thermal resistance of the cavities.

2.1.3 Convection

The convection (internal air flow in the cavity) is caused by the temperature gradient across the cavity. The convection will increase the larger the cavity thickness and temperature gradient and it will be the dominating heat transfer mechanism until a critical cavity thickness is reached. This critical thickness will vary depending on several factors, such as the number of cavities in a glazing unit and the type of gas used in the cavity.

2.1.4 Radiation

The heat radiative heat transfer is governed by the surface temperature of the adjacent glass panes and the emissivity of these surfaces. The radiation can be reduced by lowering the emissivity of the surfaces, which may be achieved by application of low-emissivity (low-e) coatings. The optical (both visible and non-visible) properties of the IGU will also be influenced when applying low-e coatings.

2.1.5 Combined effects – thermal transmittance value

Figure 1 shows calculated centre-of-glazing U_{cog}-values for typical three-pane IGUs. The effects of varying cavity thicknesses, gas-fill types and low-e coatings on the adjacent glass pane surfaces are shown. The left graph shows the centre-of-glazing U_{cog}-values for different gas fillings as a function of cavity thickness. The right figure shows U_{cog}-values for triple-pane IGUs with different gas fillings and cavity thicknesses as a function of emissivity value of the low-e coatings of the glass panes.

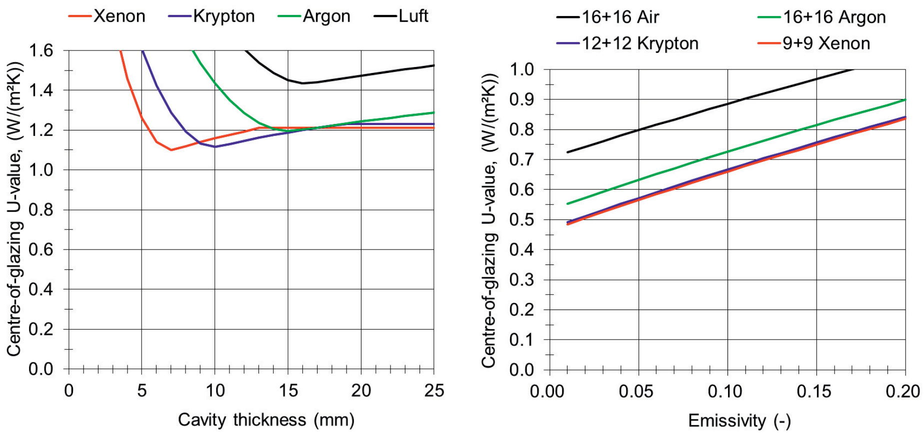

Figure 1. Centre-of-glazing U-values for a three-pane IGU as a function of cavity thickness (left) and emissivity of glass pane cavity surfaces (right). Values calculated according to ISO 15099 [15]

2.2 Optical properties

2.2.1 Total solar energy transmittance

The total solar energy transmittance is a measure of how much of the incident solar radiation hits the window aperture and is transmitted through to the interior room, which includes both the direct transmittance and the absorbed part which is re-emitted as thermal (infrared) radiation towards the interior. This is what is defined as the solar heat gain coefficient (SHGC), or solar factor (SF, g-value) for short.

2.2.2 Visible solar radiation

The visible solar radiation (T_{vis}) is calculated for the bandwidth region between 380 and 780 nm as shown in Figure 2. T_{vis} is a specific calculated value which describes the integrated value of the solar radiation which is transmitted through the glazing in that bandwidth region. It is made up of the following three main parts:

1. Direct solar radiation;
2. Diffuse solar radiation from the sky; and
3. Diffuse solar radiation reflected from surrounding surfaces.

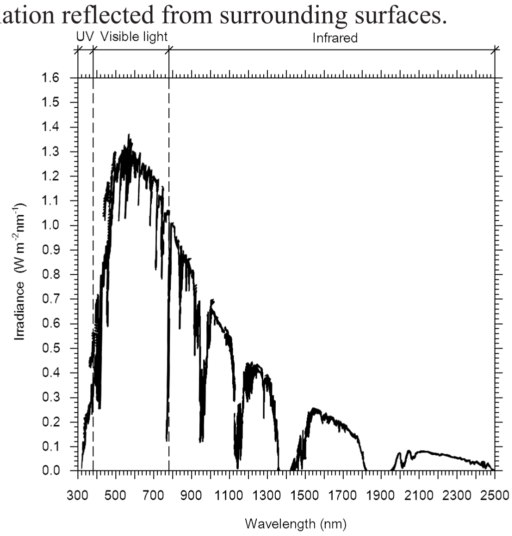

Figure 2. Reference solar spectra for direct normal irradiance and hemispherical tilted irradiance [16].

2.2.3 Transmittance factor

The transmittance factor, τ, for a glass pane is a measure of the amount of the incident solar radiation flux which is transmitted through the pane. The transmittance factor may be given for a single wavelength or an integrated value weighted and normalized with the solar spectrum in a specific wavelength section. The integrated value is often denoted as the solar transmittance (T_{sol}) for the whole solar region, for example, the visible solar transmittance (T_{vis}) for the visible solar region [7].

2.2.4 Absorbance factor

Some of the solar energy hitting a glass pane will be absorbed in the pane itself. This is expressed as the absorbance factor, α, of the glass pane. The absorbance factor may be given for a single wavelength or an integrated value weighted and normalized with the solar spectrum in a specific wavelength section. The integrated value is often denoted as the solar absorbance (α_{sol}) for the whole solar region, for example, the visible solar absorbance (α_{vis}) for the visible solar region [7].

2.2.5 Reflectance factor

The reflectance factor of a surface, ρ, is defined as the ratio of the light flux reflected from a surface related to the incident flux on the surface. The reflectance factor of a glass pane is dependent on the surface properties of the pane and the incident angle of the solar radiation. An untreated pane of float glass has a reflectance for normal incidence close to 0.08 (8 %) when adding the contribution from both glass surfaces of the pane, i.e. air/glass and glass/air for a single glass pane. The reflectance factor may be given for a single wavelength or an integrated value weighted and normalized with the solar spectrum in a specific wavelength section. The integrated value is often denoted as the solar reflectance (R_{sol}) for the whole solar region, for example, the visible solar reflectance (R_{vis}) for the visible solar region [7].

2.2.6 Combined effects – visible and total solar energy transmittance

All of these factors together govern the SHGC and T_{vis}-values for an IGU. As mentioned by Cuce and Riffat [6], the total transmittance is governed by the surface properties of the glass panes and that glass thickness effects are nearly negligible.

There are some boundaries for how large these values can be in combination. Figure 3 shows calculated values for SHGC and T_{vis}-values for a selection of IGUs using non-coated glass panes, absorbing glass panes and low-e coated glass panes using commercially available products. Based on this, a suggested line for the upper boundary of the combined values is drawn.

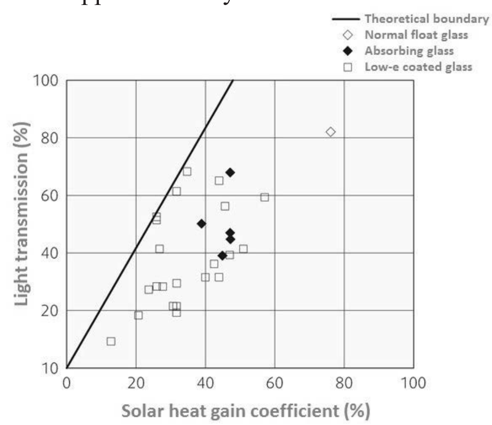

Figure 3. Theoretical boundaries for combinations of SHGC and T_{vis} of IGUs. Values are calculated according to ISO 15099 [15].

2.3 Ageing and robustness properties

The ageing and robustness properties of glazing units are important, although not a central part of the scope of this study. A more general overview of some relevant publications is nevertheless mentioned here. In order to evaluate the durability of windows, it may be beneficial to carry out accelerated climate ageing in a laboratory [17]. Various studies addressing durability issues for traditional insulated glazing units may be found in the studies by Christensen [18], Elmahdy and Yusuf [19], DS 1094.4 [20], Olsson-Jonsson [21], Wolf [22], Wolf and Waters [23], Lingnell and Spetz [24], Feldmeier [25], Penkova et al. [26] and Pilette and Taylor [27].

3 METHODOLOGY

The performance of glazing units is complex to assess. Optical and thermal performance are possibly the most important parameters but factors like aesthetics, durability, robustness and environmental impact are all crucial aspects that need to be addressed in order to make a well-functioning glazing unit and ultimately a window. The weight of the glazing units should be included as both mounting and operating the windows become cumbersome when the weight increases. For refurbishment, this is important, especially when mounting glazing units in old frames.

To limit the scope of this study, mainly the thermal performance improvement possibilities related to the thermal transmittance value (U-value) have been assessed. All values have been calculated according to ISO 15099 *Thermal performance of windows, doors and shading devices – Detailed calculations* [15] using standardised boundary conditions of 20 °C for the interior temperature and 0 °C for the exterior temperature. The surface thermal resistances of the interior and exterior surfaces of the IGUs were set to 0.04 m²K/W and 0.13 m²K/W respectively. Boundary conditions were chosen according to simplified rules in ISO 10077-1 *Thermal performance of windows, doors and shutters – Calculation of thermal transmittance Part 1:General* [28].

Further research regarding the other aforementioned aspects should also be evaluated based on the results found in this study, as the U-value is a key performance parameter, especially in cold climates.

In order to improve the thermal and optical performance of a glazing unit, several key properties of the IGUs as presented earlier can be improved. Here, a series of simulations have been performed in order to study improvement possibilities for the thermal performance as a function of the key parameters. A similar study has been carried out for the key parameters and material performance targets of typical window frames [9]. Parametric studies for centre-of-glazing U-values of IGUs with three to ten panes have been carried out using the WINDOW software [29]. The effects of varying the following three parameters for three to ten panes have been assessed:

1. Cavity thickness for up to ten glass panes;
2. Improved glass surface properties (reduction of emissivity); and
3. Gas thermal conductivity.

In addition to assessing the thermal performance, thermal stresses to the IGU caused by high temperatures in central cavities of the IGU are discussed.

4 FUTURE IMPROVEMENT POSSIBILITIES – KEY ELEMENTS

4.1 Cavity thickness

Figure 4 and Table 1 show U_{cog}-values for different cavity thicknesses as a function of the number of panes in the IGU. The U_{cog}-values are calculated under the assumption that gas thermal conductivity and surface emissivity are kept constant at 0.00516 W/(mK) (xenon at standard temperature and pressure conditions (STP) of T = 0 °C and p = 101 kPa) and 0.01, respectively. Changing the thickness of the cavities in the IGUs was found to have a substantial effect for all samples regardless of the number of panes in the glazing unit. One can observe that increasing the cavity thickness from 4 to 8 mm yielded U-value reductions of approximately U = 0.1 to 0.2 W/(m²K). A further increase of cavity thickness had a minor effect on the calculated U-values as shown in Figure 4 and Table 1. Furthermore it is clear that every additional pane added to the glazing unit has a diminishing effect in decreasing the U_{cog}-value.

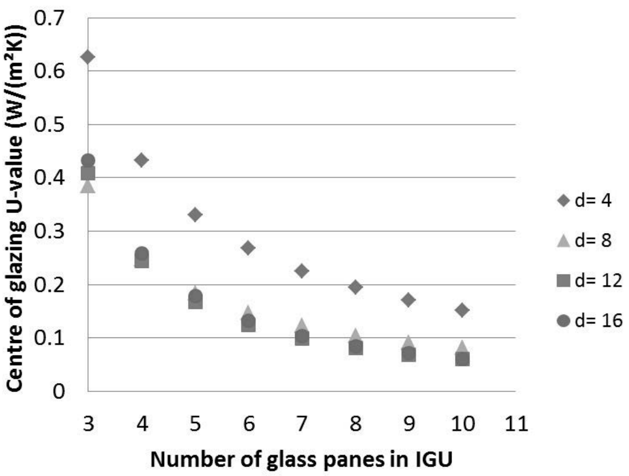

Figure 4. U-value for centre-of-glass as a function of the number of glass panes for different cavity thicknesses (d = 4, 8, 12 and 16 mm). Gas thermal conductivity and surface emissivity are kept constant at 0.00516 W/(mK) (xenon at STP) and 0.01, respectively.

Table 1. Calculated U-values (W/(m²K)) from WINDOW for three to ten glazing units with different cavity thicknesses. Gas thermal conductivity and surface emissivity are kept constant at 0.00516 W/(mK) (xenon at STP) and 0.01, respectively.

		Centre-of-glazing U-values, U_{cog} (W/(m²K))							
No. of glass layers		**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Cavity thickness (mm)	4	0.626	0.433	0.331	0.268	0.225	0.194	0.17	0.152
	8	0.385	0.247	0.183	0.146	0.122	0.104	0.091	0.081
	12	0.409	0.244	0.167	0.125	0.098	0.081	0.069	0.06
	16	0.432	0.259	0.178	0.132	0.104	0.085	0.071	0.06

4.2 Improved glazing surface emissivity

Figure 5 and Table 2 show calculated U_{cog}-values for different qualities of the low-e coating of the glass panes as a function of the number of glass panes in the IGU. The U_{cog}-values are calculated under the assumption that gas thermal conductivity and cavity thicknesses are kept constant at 0.00516 W/(mK) (xenon at STP) and 12 mm, respectively. It can be seen that reducing the emissivity of the glass panes gives a theoretical reduction potential that is small compared to that of adding additional glass panes. Reducing the emissivity further than what is available on the market today (emissivity lower than 0.013) gives a resulting U_{cog}-value reduction potential of 6 to 10 % depending on the number of panes, as shown in Figure 5 and Table 2. The reduction potential is low regardless of the number of glass panes in the IGU.

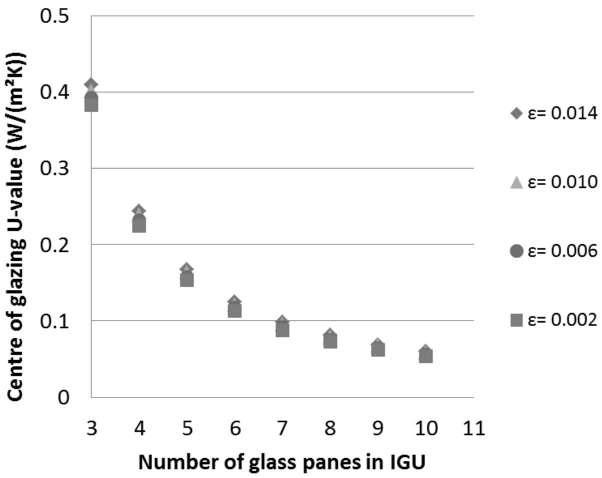

Figure 5. U-value for centre-of-glass as a function of the number of glass panes for different emissivity of the reverse side (i.e. the surface facing the interior) of each glazing layer. Gas thermal conductivity and cavity thickness are kept constant at 0.00516 W/mK (xenon at STP) and 12 mm, respectively.

Table 2. Calculated U-values (W/(m²K)) from WINDOW for three to ten glazing units with glazing layers with different glazing surface emissivity. Gas thermal conductivity and cavity thickness are kept constant at 0.00516 W/mK (xenon at STP) and 12 mm, respectively.

		Centre-of-glazing U-values, U_{cog} (W/(m²K))							
No. of glass layers		**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Glazing pane reverse-side emissivity (-)	0.014	0.409	0.244	0.167	0.125	0.098	0.081	0.069	0.060
	0.010	0.401	0.238	0.163	0.121	0.095	0.078	0.067	0.058
	0.006	0.392	0.232	0.158	0.117	0.092	0.075	0.064	0.056
	0.002	0.383	0.225	0.153	0.113	0.088	0.073	0.062	0.054

4.3 Gas thermal conductivity

Figure 6 and Table 3 show calculated U_{cog}-values for different gas conductivities as a function of the number of glazing layers in the IGU. The effective thermal conductivity of a gas filling varies, depending on several factors like cavity thickness, temperature gradients, etc. Thus, the gas thermal conductivities given in Figure 6 and Table 3 are for still gas at STP of T = 0 °C and p = 101 kPa. A conductivity of 0.005 corresponds to the thermal conductivity value of xenon at STP ($\lambda = 0.00516$ W/(mK)). In the simulations, however, convection effects are accounted for, thus reducing the effective conductivity used in the calculations. The lower thermal conductivity values could be considered as xenon at lower pressures than 101 kPa.

The calculations show that a reduction of gas thermal conductivity of the gas fillings can give a substantial reduction in the U_{cog}-values. Halving the thermal conductivity will reduce the U_{cog}-value by approximately 25 % for the three- and four-pane IGUs. For a four-pane IGU, the U_{cog}-value reduction caused by halving the gas filling improves the U_{cog}-value similar to that of adding an additional pane to the IGU.

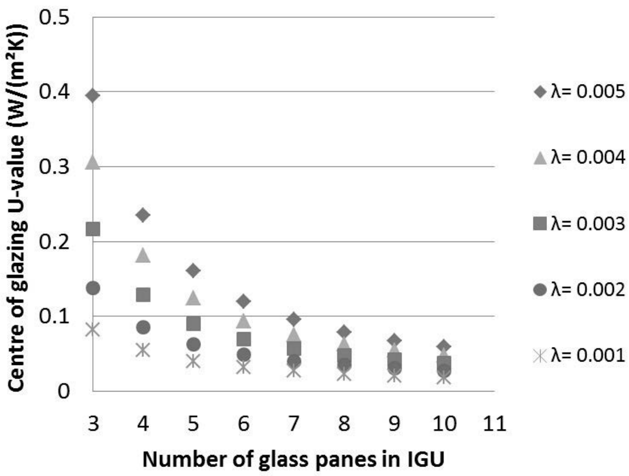

Figure 6. U-value for centre-of-glass as a function of the number of glass panes with different gas thermal conductivities. Surface emissivity and cavity thicknesses are kept constant at 0.014 and 12 mm, respectively.

Table 3. Calculated U-values (W/m²K) from WINDOW for three to ten glazing units with glazing layers with different gas thermal conductivity and number of panes. Surface emissivity and cavity thicknesses are kept constant at 0.014 and 12 mm, respectively.

		Centre-of-glazing U-values, U_{cog} (W/(m²K))							
No. of glass layers		**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Gas thermal conductivity at STP (W/(mK))	0.005	0.395	0.235	0.161	0.120	0.095	0.078	0.067	0.059
	0.004	0.306	0.181	0.124	0.093	0.075	0.063	0.054	0.048
	0.003	0.217	0.129	0.090	0.069	0.057	0.048	0.042	0.037
	0.002	0.138	0.085	0.062	0.049	0.040	0.035	0.03	0.027
	0.001	0.082	0.054	0.040	0.032	0.027	0.023	0.02	0.018

4.4 Temperature peaks in centre-layers

Calculations performed in WINDOW show that the surface temperatures of the middle glazing layers in multi-pane IGUs can reach high temperatures with incident solar radiation levels typical for summer days.

Modelling a four-layer window with existing glazing technology gives maximum temperatures of approximately 40 °C for standardised boundary conditions according to the European Committee for Standardization (CEN) of 20 °C for the interior temperature and 0 °C for the exterior temperature with no incident solar radiation flux. Surface thermal resistances of the interior and exterior surfaces of the IGUs were set to 0.04 m²K/W and 0.13 m²K/W respectively. A worst-case scenario for a four-pane glazing unit using National Fenestration Research Council (NFRC) summer conditions, $T_{interior}$ = 24 °C, $T_{exterior}$ = 32 °C and an incident solar radiation flux of 783 W/m² gave a maximum surface temperature for the middle glass layer of 74.3 °C.

A worst-case scenario for a ten-pane glazing unit with xenon gas fillings, low-e coatings with emissivity 0.013 and 12 mm cavity thicknesses using CEN summer conditions, $T_{interior}$ = 25 °C, $T_{exterior}$ = 35 °C and an incident solar flux of 500 W/m² [15] gave a maximum surface temperature of 130 °C on the interior side of glazing number 4 (counted from the outside). When simulating the same IGU using NFRC summer conditions $T_{interior}$ = 24 °C, $T_{exterior}$ = 32 °C and an incident solar radiation flux of 783 W/m², the maximum surface temperature for the middle glass layer (layer number 5 counted from the outside) was 170 °C.

Internal temperatures in multilayer structures might be a limiting factor in terms of durability, in particular for thin polymer-based intermediate layers, and should be further studied.

5 SYSTEMS – MULTILAYER GLAZING UNITS

There are several producers of multilayer glazing units using different technologies. Multilayer windows as discussed here can be divided into the following three main categories:

1. Multilayer all-glass products:
    a. Regular insulated glazing units (IGU).
    b. Thin glass technology.
2. Outer glass layers with suspended polymer foils.
3. All-polymer-based products.

The following section is an overview of some producers of systems and components for multilayer glazing units fitting into the three categories mentioned above.

5.1 Traditional insulated glazing units

By far the most common construction for a modern IGU uses glazing layers approximately 4 mm or thicker. Cavities are gas-filled and a selection of the glass panes is coated with low-e films. These films are typically placed on glazing surface number 3 (counting from the outside) in a two-pane window, as shown with dashes in Figure 7. Glazing surface numbers 2 and 5 are typical placements for low-e coatings in three-pane IGUs.

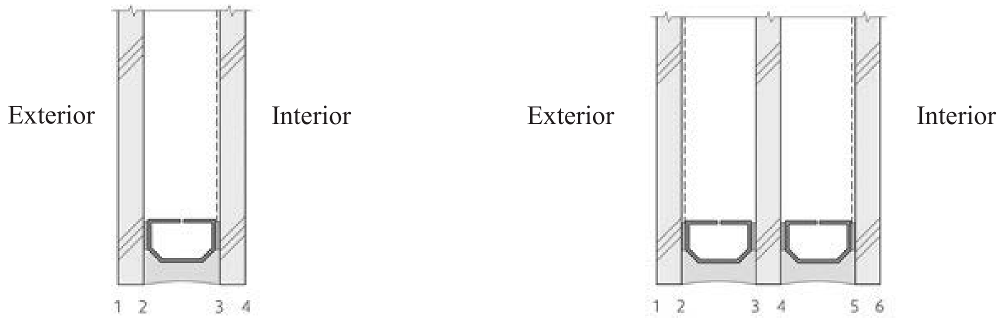

Figure 7. Typical placements of low-e coatings, depicted as dashes.

The low-e coatings are vital in reducing U-values of an IGU, even if the low-e coatings will, in general, result in a reduction of the visible solar transmittance of the IGU. The best-performing commercially available low-e coating has an emissivity of 0.013 as declared by the producer for the Pilkington Optitherm S1 [30].

5.2 Multilayer *all-glass* products

Multilayer all-glass products are products where the entire unit (i.e. the transparent parts) are made of glass. The traditional IGUs belong to this category. New products using thin glass layers with thicknesses as small as 0.1 mm are available on the market. The benefit of using thin intermediate glass layers is primarily that of weight reduction of the IGU. A thinner glass pane will also absorb less solar energy, thus maintaining higher solar gains and visible solar transmittance values than a thicker glass pane.

Superwindows is the only company with products found to be commercially available on the market today. They produce two different IGUs with as many as ten intermediate glass layers.

The glass currently being used in the intermediate layers are 200 µm thick. Normal 4 mm float glass panes are used as the inner and outer panes. The STACK system has a total thickness of 160 mm and uses ten intermediate layers placed parallel to the inner and outer panes as shown in Figure 8. The U-value of the glazing unit including spacer and edge loss effects (excluding window frames) has been measured to 0.3 W/(m²K) according to the producer [31]. The Tweed system, also shown in Figure 8, has the same total thickness of 160 mm but uses five curved layers as intermediates. The producers state that the geometry of the foils will be an effective measure in minimizing convection effects in the cavities. The U-value of this glazing unit has been measured to 0.72 W/(m²K) according to the producer [32].

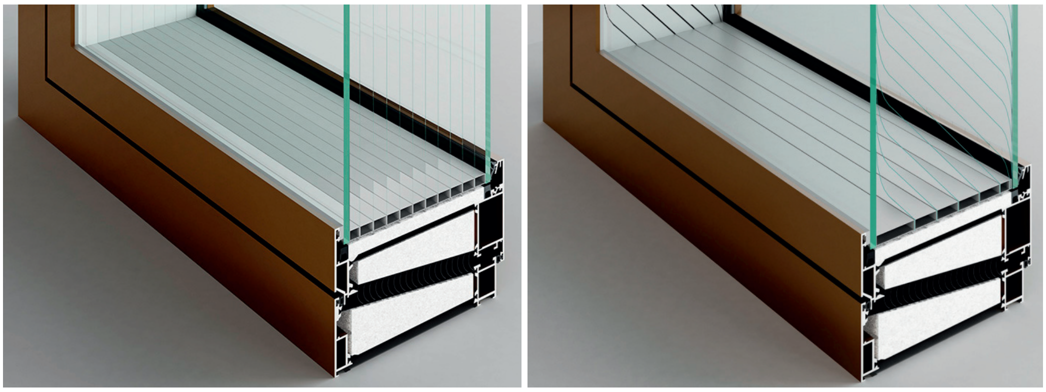

Figure 8. Cross-section of the Superwindow INVIS 160 STACK (left) and the INVIS 160 TWEED (right) [31, 32].

However, there are several producers that may supply thin glass layers which could be suitable for such a technology. This will be further elaborated in the following section.

5.3 Multilayer *glass/polymer* combination products

Multilayer glass/polymer combination products are glazing units similar to the all-glass units where the exterior structural (i.e. load-bearing) layers are made of traditional glass. However, instead of intermediate glass layers, polymers (or similar materials) are used to create the multi-cavity glazing unit.

Southwall [33] is one of two producers which were found to manufacture windows using this technique. Eastman procured the brand in July 2012 [33] though prior to that the windows were sold under the Serious Windows brand. They produce a five-pane “QUAD chamber” window, SGQ TC88, with three intermediate heat mirror foils (76 µm thick) and xenon fillings in the cavities, as depicted in Figure 9. This window has a declared U-value of 0.46 W/(m²K), an SHGC of 0.39 and a T_{vis} of 0.5 [34]. Southwall declares that their product “complies with thermal ageing and ultraviolet exposure test per ASTM D-882, G-53” [35].

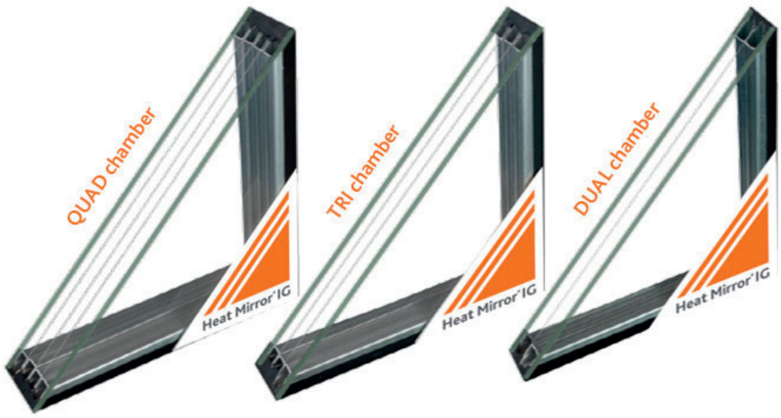

Figure 9. Glass/polymer combination windows using one, two and three heat mirror films [36].

Visionwall [37] is the other producer of suspended film-based windows. They market what they call a 4-Element Glazing System. Two suspended polyethylene-films (PET-films) with low-e coatings are mounted in-between the outer 4 mm glass panes, as depicted in Figure 10. This gives a window with a U-value of 0.82 W/(m²K) (including frames), an SHGC of 0.26 and T_{vis} of 0.46 [37]. The PET-films are supplied by DuPont [38].

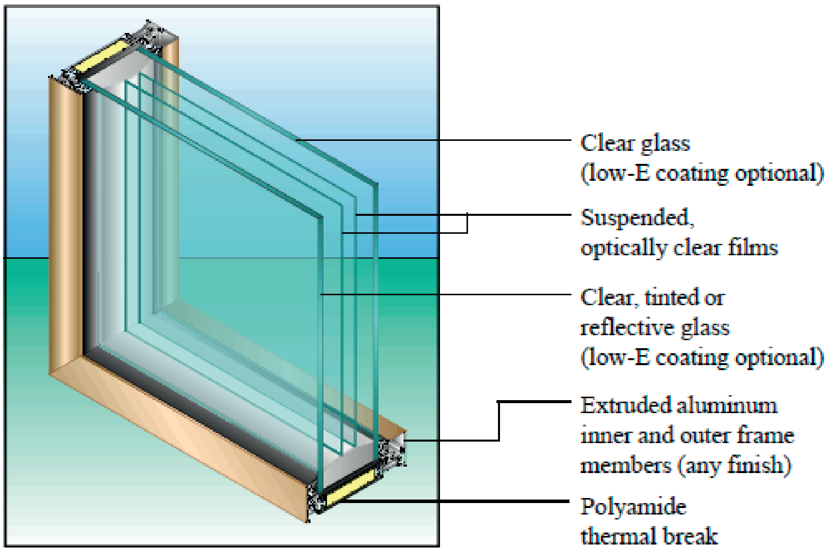

Figure 10. The Visionwall 4-Element glazing system [37].

The structural stability of a multilayer glass/polymer combination system like this is dependent on several factors. Existing products using polymer-based intermediate layers have been prone to shrinking and/or swelling of the polymer. This phenomenon affects the visible qualities of the window as it creates wavelike patterns in the foils. Proper installation of the foils is vital in order to provide durable windows. No literature describing ageing and robustness have been found for the Visionwall products.

5.4 Multilayer *all-polymer* products

The third category of multilayer IGUs is entirely made of polymers (plastic).

Sekisui [39] is a Japanese company which manufactures a system they call Air Sandwich. The entire glazing system is made of plastic and it is primarily designed for refurbishments of existing windows. Figure 11 shows an illustration of the Air Sandwich in front of an existing window. The Air Sandwich is specially made to specific measurements and glued on to the inner side of the existing window. The system is not exported outside Japan and it has to be mounted by personnel approved by the producer. In the current commercially available version, five air layers are sandwiched in-between the outer plastic shell. The unit is 4 mm thick in total and has a declared U-value of 3.4 W/(m²K) and a T_{vis} of 0.60. A single low-e coated glass pane added a certain distance from the inner pane of the existing window would yield a better U-value reduction than the Air Sandwich system.

Figure 11: Illustrating the Sekisui Air Sandwich element in front of an existing window [39].

5.5 Product summary

Key parameters of the various window systems are given in Table 4, and key properties for the different film technologies are given in Table 5.

Table 4. Key parameters for the glazing systems. IGU weight is given for weight of glass/foils only. Weight of spacers is not included.

Window type / manufacturer	Centre-of-glazing U_{cog}-value (W/(m²K))	SHGC (-)	T_{vis} (-)	Weight of IGU (kg/m²)	Thickness of IGU (mm)	Reference
3-pane traditional (4E-16Xe-4E-16Xe-4) with low-e and xenon gas filling	0.43	0.35	0.58	26	36	Generic from International Glazing Database (IGDB).[1] http://windowoptics.lbl.gov/data
4-pane traditional (4E-12Xe-4E-12Xe-4E-12Xe-4) with low-e and xenon gas filling	0.24	0.29	0.48	35	52	Generic from IGDB. http://windowoptics.lbl.gov/data
10-pane traditional with low-e and xenon gas filling	0.07	0.131	0.186	88	148	Generic from IGDB. http://windowoptics.lbl.gov/data
All-glass: Superwindow	0.30			20	160	http://superwindows.eu/en/
Glass/polymer: Southwall SGQ TC88	0.46	0.39	0.5	18		http://www.eastman.com/ Pages/southwall_technologies.aspx

[1] The IGDB is a collection of optical data for glazing products. Spectral transmittance and reflectance is measured in a spectrophotometer and contributed to the IGDB by the manufacturer of the glazing product subject to a careful review. Most commercially available products are registered here.

Glass/polymer: Visionwall 4-Element	0.82 (whole window)	0.26	0.46	18		http://www.visionwall.com /res/pdf/VCorpBrochure.pdf.
All-polymer: Sekisui Air Sandwich	3.4			8		http://www.sekisuichemical.com/

6 COMPONENTS – THIN GLASS AND FILM TECHNOLOGIES

Maintaining the favourable thermal and optical properties while keeping the weight of the multilayered windows at an acceptable low level can be achieved by using non-structural intermediate layers. Applications using polymer-based foils and thin glass layers have been found in the literature.

6.1 Ultra-thin glass products with thicknesses < 0.1 mm

Asahi Glass [40] manufactures what they claim to be the thinnest available glass produced by the float process on the market today. The glass is an alkali-free and flexible glass sheet with a thickness of 0.1 mm [41]. The glass can be supplied in 1 m wide rolls, as shown in Figure 12, in practically unlimited lengths.

Figure 12. A roll of the flexible ultra-thin glass from Asahi AGC-glass [41].

Corning [42] is another commercially available ultra-thin glass layer producer. Their 0.1 mm thick Willow glass [43] is similar to the Asahi AGC-glass. Transmission spectra curves for different glass thicknesses are shown in Figure 13.

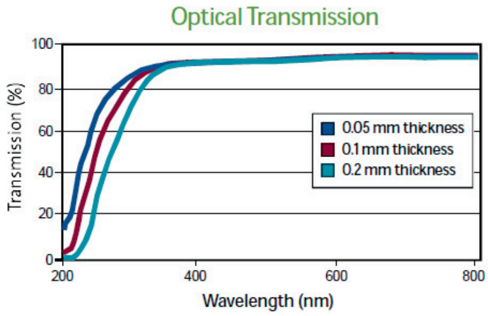

Figure 13. Optical transmission spectra for different glass thicknesses of the Corning Willow glass according to the producer [43].

Schott [44] also produces such ultra-thin glass layers [45] with thicknesses in the range of 25–100 μm. They can deliver glass in 0.5 m wide rolls.

PGO [46] is a German thin glass supplier, with their D263T glass being their thinnest available with thicknesses between 0.03 and 0.21 mm [47]. The glass itself is produced by Schott. It has high light transmission values, as shown in Figure 14.

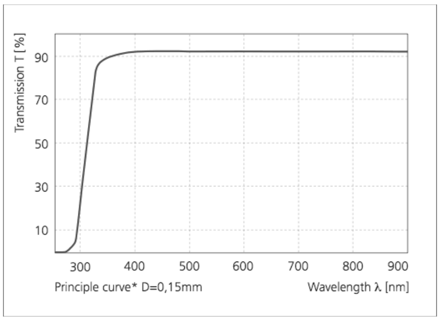

Figure 14. Transmission spectra for the D263T glass according to the producer [48].

It is worth noting that one aspect that is not covered in the producers' fact sheets is the possibility of applying low-e coatings to such thin films.

6.2 Suspended films – polymers

DuPont Teijin Films [38] is one of the producers of thin film technology currently being used in windows. They supply polyester films with different coatings [49] as well as the foil that is used in the Visionwall system (described in chapter 4.3). The foil is 51 µm thick and has a low-e coating with an emissivity of 0.66 [37].

Heat Mirror [33] is a foil produced by Eastman under the Southwall technologies brand. The Heat Mirror film is 76 µm thick and can be delivered with a low-e coating. Emissivity values as low as 0.02 can be obtained according to the data given in the IGDB [30]. The Heat Mirror foil has been used in 6500 windows in the Empire State Building in New York [50].

Table 5. Product summary of the thin glass and polymer non-structural centre-glazing layers.

Film type / Brand name	Glass	Polymer	Low-e coating?	Thickness (µm)
AGC-glass	X		No	100
Schott	X		No	25–100
Corning	X		No	100
DuPont		X	Yes (0.66)	51
Heat Mirror		X	Yes (0.02)	76

7 CONCLUSIONS

There is a lack of scientific work regarding thin glass and/or polymer-based non-structural intermediate layers in IGUs. A selection of products using only glass, glass in combination with polymer-based intermediate layers and all-polymer-based units have been identified in the market.

Simulations with the aim of identifying the parameters that play the key role in improving thermal performance have been carried out. Increasing the number of glass panes in the IGU yields U-value reductions that decrease for each added glass pane. Further research should be coupled with life cycle assessments in order to investigate if there is an optimal number of panes when embodied energy is also accounted for. Further improving the low-e surface coatings of panes in an IGU yields little improvement possibilities compared with today's state-of-the-art technologies. Cavity thicknesses between 8 and 16 mm were found to be optimal for IGUs with four or more panes. Only small variations within the 8 to 16 mm range were found. Hence, cavities can be kept at 8 mm in multilayer IGUs in order to keep the total thickness of the IGU as thin as possible. Reducing the gas thermal conductivity was found to have the largest impact on the U-value. The effect gets less pronounced with an increased number of panes in the IGUs.

In addition to the thermal performance of the glazing units, optical properties, aesthetics, ageing properties and robustness should be further studied before the use of such multilayer IGUs may be recommended. Preliminary numerical simulations have demonstrated that thermal stresses to the glazing units due to high cavity temperatures can pose a problem for the robustness and lifetime of such units. However, the reliability of these results should be treated with caution and further studies and validation experiments of the algorithm used in the software should be carried out.

Further studies should be carried out keeping the following factors in mind:

- Improved solid materials (i.e. lowered thermal conductivity and/or weight of glass or polymer layers);
- Geometry of intermittent layers;
- Reduce weight without comprising the performance;
- Prevent/slow the ageing processes; and
- Reduce/prevent temperature peaks in central layers.

8 ACKNOWLEDGEMENTS

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