IOP Conference Series: Earth and Environmental Science

Simulation and control of shading systems for glazed facades

IOP Conf. Series: Earth and Environmental Science **352** (2019) 012069 doi:10.1088/1755-1315/352/1/012069

Simulation and control of shading systems for glazed facades

G Chaudhary[1], **F Goia**[1], **S Grynning**[2]

[1] Norwegian University of Science and Technology, Faculty of Architecture and Design, Alfred Getz vei 3, 7034 Trondheim, Norway
[2] SINTEF Building and Infrastructure, Høgskoleringen 7b, 7465 Trondheim, Norway

francesco.goia@ntnu.no

Abstract. This paper presents a simulation study on the use of shading devices in highly glazed facades in the context of zero emission buildings (ZEB) located in a Nordic climatic context. Shading devices have the task to control different uses of solar energy (solar gain for passive solar heating and daylighting) and to avoid cooling load, and to find the best strategy (i.e. to optimize the overall performance) for controlling shading devices is not trivial.
Different control strategies for the activation of the shading devices (venetian blinds) are simulated, and their performance calculated in this study through a dynamic whole-building simulation tool (EnergyPlus). The results of the simulation studies show that it is possible to achieve very high performance and balanced use of solar energy (for passive solar heating, daylighting), without occurring in too high cooling load, even in the case of fully glazed facades. The optimal strategy for shading activation is not straightforward, and different strategies should be recommended during the year to assure an overall optimal performance.

1. Introduction

Fully transparent façades based on curtain-wall systems have not been traditionally considered a sustainable solution for office buildings in the Nordic climate because heat loss through the glazed façade would have led to high energy use for heating and high thermal discomfort for the user.

Furthermore, the large transparent area, coupled to the relatively high-density of internal gain typical of an office building, would have caused cooling load not only in the summer months, but even in the mid-seasons. However, a previous studies [1] already showed that, when looking at the total energy performance of the building (including heating, cooling, and lighting), a Window-to-Wall Ratio (WWR) of up to 0.80 is not impairing the energy performance of a low energy building located in the Nordic context (for a south exposed façade), provided that it is realized with best available technologies for façade systems and it is equipped with shading devices controlled in a dynamic way.

The current development of curtain-wall façade technologies has led to market availability of outstanding façade systems, characterized by a thermal performance close to that of more conventional envelope solutions based on opaque walls and windows, coupled with shading systems capable of properly managing solar gains. Furthermore, advanced façade systems characterized by an optimal control of shading system can contribute to increase the daylight autonomy and keep the risk of glare discomfort, evaluated through the metrics $UDI_{>2000}$ [2], within a relatively safe area.

Previous investigations have thus proved the feasibility of a façade with a large WWR in a Nordic climate, as well as the need of a case-by-case investigation of the optimal control strategy for the shading systems, as increased energy demands can happen when an improper shading strategy is chosen [3]. However, there are not studies dedicated to curtain-wall solutions (so with very high

WWR) showing the implication of different control strategies for the shading, and only fully mechanical climatized buildings were investigated, while the evaluation of the performance of an office building only equipped with the heating plant has not been analyzed.

The investigation presented in this paper extends the analysis presented in the previous study [1] and looks at the operational energy performance and visual comfort of different façade configurations for a low energy office concept building. The aim has been to investigate the energy demand for heating and cooling as well as daylight conditions in the buildings as function of glazing area (conventional façade vs. curtain-wall façade) and several shading strategies. The concept building has previously been used as a case building for conceptual studies of life cycle performance in a zero-emission building context and more thorough description of the baseline building can be found in [4].

The study comprises the analysis of both a fully mechanically climatized building (i.e. with mechanical heating and cooling), and of an office building characterized by only mechanical heating, addressing the research question whether a fully glazed façade can compete or not in terms of energy and visual comfort with a more conventional façade, composed by (large) windows and opaque walls.

2. Methods

2.1. Case study building and facade technologies

The research activity has been carried out through the extensive use of *one* building performance simulation *tool,* EnergyPlus™ (version 8.5) [5], and the use of a case study building whose behavior is assumed to be representative of that of any conventional office building, even if the latter one is not presenting the exact same layout. This assumption is based on the adoption of a case-study building defined by other researchers [4], who developed it with the scope of making available a reference construction configuration for performance analyses a low energy office building in a Nordic context.

The case-study building used in the study is a 4-storey high office building, with a rectangular footprint of approximately 17 x 30 meters, with long facades facing south and north. Each floor has a heated floor of 495 m², giving a total area of 1980 m². The case study building is constructed according to the requirements in the passive house standard for non-residential buildings [6], with the following thermal transmittance values for the different components: external walls U = 0.12 W/m²K; external roof: U = 0.09 W/m²K; floor against basement: U = 0.11 W/m²K; windows: U = 0.75 W/m²K; doors: U = 0.75 W/m²K; normalized thermal bridge value phi = 0.03 W/m²K.

For the scope of this study, two twin buildings with a different WWR configuration have been modeled and simulated:

- a baseline WWR solution (WWR nearly 0.35) with a baseline façade, as described in [4]; and
- a fully-glazed solution representing a curtain-wall façade, with a WWR of nearly 0.95.

The baseline building has a total window and door area of 456 m². The windows used in this façade configuration are made of an aluminum insulated frame (with U-value of 1.280 W/m²K), positioned in the middle of the wall in order to reduce the thermal bridge effect. The window-wall junction thermal bridge value is 0.015 W/mK. The window is equipped with a triple-pane glazed unit, with a centre-of-glazing U-value of 0.72 W/(m²K), solar factor (g-value) of 0.716, and visible transmittance of 0.740. The U-value of the window, depending on its size, is in the range 0.65 to 0.75 W/m²K.

The curtain-wall façade building has a total window and door area of 750 m² and makes use of a curtain wall system characterized by a frame transmittance of 1.410 W/(m²K). The glazing is the same as for the reference building. Both the reference façade and the curtain-wall façade are equipped with an interpane shading system, a venetian blind that can coupled with different control strategies.

2.2. Simulation settings

A virtual numerical model of the case study building in the two configurations has been developed in *EnergyPlus* to assess the energy performance. The thermal zoning of the building has been realized by keeping together coherent areas but still preserving representative rooms (such as the single office room towards the south and towards the north), leading to a total of 27 zones.

The EnergyPlus model *Ideal load system* was used to calculate the room size energy use without recurring to modeling the full HVAC system (which depends on the type of building and increases the number of variables in the study). Within this system, Differential Dry Bulb Outdoor Air Economizer and a Sensible Heat recovery system was selected to simulate the adoption of best available technologies in connection to ventilation (i.e. a heat recovery system with the possibility to bypass the device). Heating was scheduled to run the all 8670 hours of the year if necessary, whereas cooling (for fully climatized building) was scheduled to run only during working hours, if necessary. The heating setpoint was 21 °C with a setback of 2 °C (for unoccupied hours in the office) and the cooling setpoint was 26 °C, but cooling was turned off during unoccupied hours so had not setback temperature.

As the plants of the building was not modelled in detail, since this would have required several additional assumptions that might have limited the generalisation features of the analysis, an ideal heating and cooling plant, characterized by constant coefficient of performance (COP) values, was assumed. The values for the COP were as follow: for heating a COPh = 3 and for cooling a COPc = 4.

To allow a simple sensitivity analysis over influence of different COPs, two additional values for COPh and COPc were considered too: a COPh = 2.5 and of 3.5; and a COPc = 3 and 6).

When the cooling is not activated because of unoccupied space, or when a configuration without mechanical cooling is tested, free cooling in the form of ventilation was simulated. This ventilation was simulated in form of night ventilation from 24:00 to 7:00 am and full 24 hours on weekends (when the office was unoccupied). V. Geros et al. [7] measured night ventilation flow rate (air change per hour, ACH) varying from 4 to 11 h^{-1} in single sided ventilation, whereas M. Kolokotroni et al. [8] mentions that low value of 5 h^{-1} for night ventilation was consistent with ventilation rates achievable through single-sided openings in offices. Considering the above studies, settings were implemented so that a (natural) ventilation flow (with outdoor air) of 2 ACH would be assured in zones if indoor temperature is above 26 °C and the outside temperature is higher than 13 °C (to avoid undercooling).

Furthermore, at the end of the study a parametric analysis was carried out to analyze the effect of varying the ACH rate for free cooling ventilation rate on overheating degree hours (ODH) during the occupied hours. The ACH was varied from 0.5 to 10 h^{-1}. This approach can be found in literature in similar studies, for example by N. Artmann et al. [9], who studied ODH above 26 °C (ODH_{26}) as a function of air change rate (0.5–32 ACH) during night-time ventilation, or by R. Ramponi et al [10] carried out a sensitivity study by imposing constant night ventilation rates varying from 0.5 to 20 h^{-1} to analyze the energy saving potential of night ventilation.

The building follows the occupancy schedule of a typical daytime office. In the occupied zones per person occupies 5 m^2 during working hours in weekdays, i.e. 08:00 to 19:00, Monday to Friday, whereas for weekends and holidays the whole building is considered unoccupied. Activity level was set to 111 W/person, following the recommendation contained in the ASHRAE Fundamental 2011 correspondent to office sitting activities, and electric equipment releasing, during occupied hours, to 4 W/m^2 [11]. The lighting in the building was on during occupied hours, with an installed lighting power density is 3 W/m^2, which is dimmed 0 to 100% depending on the daylight availability in the zone to reach the illuminance setpoint of 500 lux.

2.3. *Performance metrics*

The performance of glazed façade was analyzed using three different metrics referred to two domains: thermal environment and visual environment.

The direct effect of the façade configuration on energy demand of the building was analyzed by comparing annual heating, cooling and artificial lighting energy consumption expressed in kWh/m^2.

The time profile of the room indoor air temperature is used to assess the performance of the shading strategies for those scenarios where the mechanical cooling is turned off. The aim of this simple parameter is to assess whether or not the combination of natural (night-time, primarily) ventilation and high-performance façade itself is capable to maintain the required thermal comfort conditions. In the context of this study, a temperature in the range 20 °C and 26 ºC is considered to be comfortable, while a temperature up to 28 °C is still considered acceptable. This assumption is supported by the body of knowledge available in the literature and standards (for example [12]) that demonstrates how temperature higher than 26 ºC can still be perceived as comfortable by the user in case of a non-mechanically ventilated building, and in combination with high outdoor air temperature (i.e. during the summer season). In the scenarios without mechanical cooling, the annual hourly values of the indoor air temperature exceeding 26 ºC and 28 ºC were used to assess the risk of discomfort linked to overheating of the building. The number of hours, during the occupancy period (i.e. excluding time outside the set working hours and weekends), when the indoor temperature exceeded the two threshold values were counted.

Finally, the *Useful Daylight Illuminance (UDI)* [13] has been used to analyse the implication on the visual environment. The UDI measures how often the daylight on the working plane is within a specific illuminance range, and four different UDI are used, following the range limits proposed by Nabil and Mardaljevic [13]:

- $UDI_{<100}$ – insufficient to be the sole source or to contribute significantly to artificial lighting;
- $UDI_{100–500}$ – effective either as the sole source of illumination or with artificial lighting;
- $UDI_{500–2000}$ – often perceived either as desirable or at least tolerable;
- $UDI_{>2000}$ – likely to produce visual or thermal discomfort, or both.

While energy (both thermal and electric) use can easily be obtained as an output from the simulation engine, there is no direct output for UDI in EnergyPlus, and a dedicated subroutine implemented in the EnergyPlus Erl language was developed to compute the different UDI values.

2.4. Overview of the simulations and scenarios

The performance analysis of the two façade systems was assessed in a comparative way, using the reference façade configuration (the original one form the ZEB Concept Office Building) as a baseline to measure the impact of different configurations.

The general performance analysis is carried out by comparing four different scenarios, described in Table 1, where the following nomenclature was used: REF and FG means reference (Baseline) and fully glazed façade configuration, respectively; noSHADING and bestSHADING, refer to the lack of integration or the integration (best strategy) of shading systems, respectively.

However, the simple integration of a shading device is not enough to determine the performance of the building, as this depends on how the shading device is controlled. To deepen this aspect and to take into consideration a control strategy that leads to a (nearly) optimal performance, a parametric analysis on different control strategies was necessary. Five different shading control logics where therefore simulated and used to select the best shading control strategy.

The six different control logic scenarios (S1...S6) used in the analysis are:

1. *Shading is on when solar radiation incident on the window exceeds a SetPoint* (W/m^2) and schedule, if specified, allows shading – different setpoint values are tested.
2. *Shading is on if zone air temperature in the previous timestep exceeds a SetPoint* (ºC) and schedule, if specified, allows shading – different setpoint values are tested.
3. *Shading is on if zone cooling rate in the previous timestep exceeds a Setpoint* (W) and schedule, if specified, allows shading – different setpoint values are tested.
4. *Shading is on at night and on during the day if the solar radiation incident on the window exceeds Setpoint (W/m^2) and if the zone cooling rate in the previous timestep is non-zero.*
5. *Shading is on if illuminance on a reference point is higher than a threshold value and-or zone air temperature is higher than a threshold value:* This shading scenario is not naturally implemented in EnergyPlus, and it was created in the EMS module. The threshold values used in this case are 2000 lux (illuminance-based control) and 25 ºC (zone air temperature).
6. *Shading is on when scheduled.* In this shading scenario, the shading control is based on the single reading of the illuminance value on the indoor horizontal plane. In practice, such a strategy is implemented through a pre-set schedule (calculated with a separated simulation run) that identifies the hours of the year when the indoor illuminance would exceed (if shading were not lowered) the threshold value of 2000 lux.

7. Table 1. Key features of the building systems and components of the case study building

Scenario Name	WWR		Integrated shading system	
	Reference	Fully glazed	No	Yes
REF_noSHADING	✔		✔	
REF_bestSHADING	✔			✔
FG_noSHADING		✔	✔	
FG_bestSHADING		✔		✔

3. Results

3.1. Building with mechanical heating and cooling

3.1.1. Thermal environment and energy performance

In Figure 1 the overview of the results from the simulation study is presented in terms of energy use for heating, cooling, and artificial lighting. The energy use for heating (blue bar) and cooling (orange bar) is plotted for different COPs, using the error bar – the bar value is the one for the reference case, where COPh = 3 and a COPc = 5; the top value of each error bar represents the energy use for a COPh = 2.5 and COPc = 4; the bottom value of each error bar represents the energy use for a COPh = 3.5 and a COPc = 6). In Figure 1 only the results for the best shading strategy are reported.

The simulation demonstrates that the gain in reducing the energy for lighting thanks to a larger daylight income in the building with curtain wall far overcomes the very minimal worsening of the energy use for heating (almost negligible) and of the energy use for cooling (which instead almost double, though it remains below 1.5 kWh/m^2 even in the worst cases).

It is also shown that for the conventional, reference office building, the use of shading devices does not necessarily lead to a general better behavior, as the cooling energy reduction achieved through the activation of the shading devices is counterbalanced by a slight increase in the energy use for lighting, and a more noticeable increase in the energy use for heating – due to the missing solar heat gain.

Conversely, the use of shading devices is always beneficial in the case of a curtain-wall system, since it only marginally leads to an increase in the energy use for artificial lighting, but drastically reduces the energy use for cooling.

3.1.2. Shading strategy influence and visual environment performance

The efficient use of shading systems heavily relies on the identification of a correct control strategy, as these systems can provide adequate protection against cooling loads, and comfortable visual conditions only if continuously controlled, and controlled according to a suitable control logic. The identification of the most suitable control strategy is not straightforward as shading systems are dealing with competing uses of solar energy. It is very common to see that while one particular energy use is reduced by a certain shading strategy, a competing one increases.

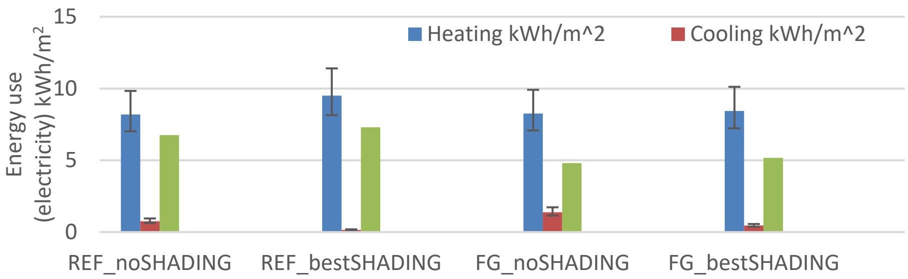

Figure 1. Comparison between Baseline building (REF), with no shading (noSHADING) and shading (bestSHADING) system, and the correspondent configuration for the fully glazed building (FG).

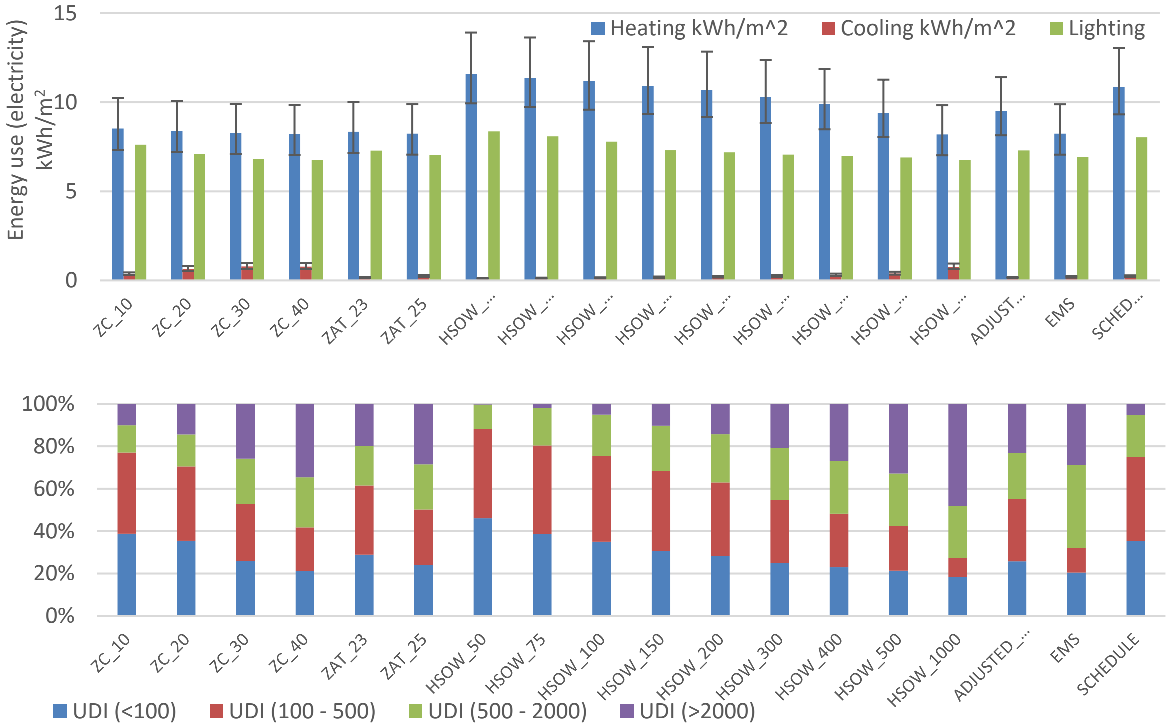

Figure 2. Comparison between different shading strategies in terms of energy use (top) and UDI (bottom), for the Baseline building with reference facade.

Figure 3. Comparison between different shading strategies in terms of energy use (top) and UDI (bottom), for the building with curtain wall facade.

In Figures 2 and 3, the energy use for heating, cooling, and artificial lighting for different shading strategies are compared, as well as the corresponding UDI values for the representative, south-exposed office space. By comparing the reference and the fully glazed solution in terms of shading control logic, it appears that the performance of the control logic is relatively insensitive to the WWR.

For both the cases, as expected, strategies that points towards minimisation of cooling energy use lead to higher requirements for lighting and heating, and the other way around. A suitable compromised solution, assuring both relatively low energy use for cooling, small increase in energy use for heating, and low value for $UDI_{>2000}$ (connected to the risk of glare discomfort) can be based on setting a control on the zone temperature (for example 23 °C, code ZAT_23). Strategies based on the level of irradiation on the façade (codes HSOW) are effective in controlling cooling energy use but lead to a significant increase in the energy use for heating. More advanced strategies combining controls based on thermal and lighting objectives (code EMS) just slightly outperform a simple control strategy but leads to an increased risks of glare discomfort. The strategy aiming at minimising glare discomfort risk (code Schedule) achieves the desired performance but with an increase in the energy use for heating of around 50%, compared to other optimal strategies.

3.2. Building without mechanical cooling

In Figure 4 the performance of different configurations (same as in Fig. 1) of the façade of the office building analysed are presented, for a building with only mechanical heating systems. As for the twin building equipped with the cooling plant (Fig. 1), it is shown that the fully glazed configurations are completely comparable in terms of energy performance to the reference configurations based on a large window layout, with a significant decrease in the energy for artificial lighting.

Without a cooling plant, it is however strictly necessary that the fully glazed building is equipped with shading systems, otherwise the number of hours outside the comfort zone, in a south exposed office, will be unacceptable (Fig. 4, bottom). When equipped with a shading system, it is possible to limit the discomfort hours (using the best, year-round strategy) to little less than 150 h. Almost 75% of these hours happens in July – i.e. when the office is not in full use due to summer holidays – and when a different, dedicated strategy could be implemented to completely avoid overheating. In the current simulation study the shading systems are controlled in July as during the entire year. However, if, for example, in the scenario FG_bestSHADING (with 2 ACH free night cooling), the venetian blinds are continuously closed in July, due to unoccupied spaced, the annual hours in the range 26 °C to 28 °C and exceeding 28 °C become 239 (from 439) and 91 (from 149), respectively. Hours exceeding 28 °C outside July are 41, and happens primarily in August and in the late afternoon.

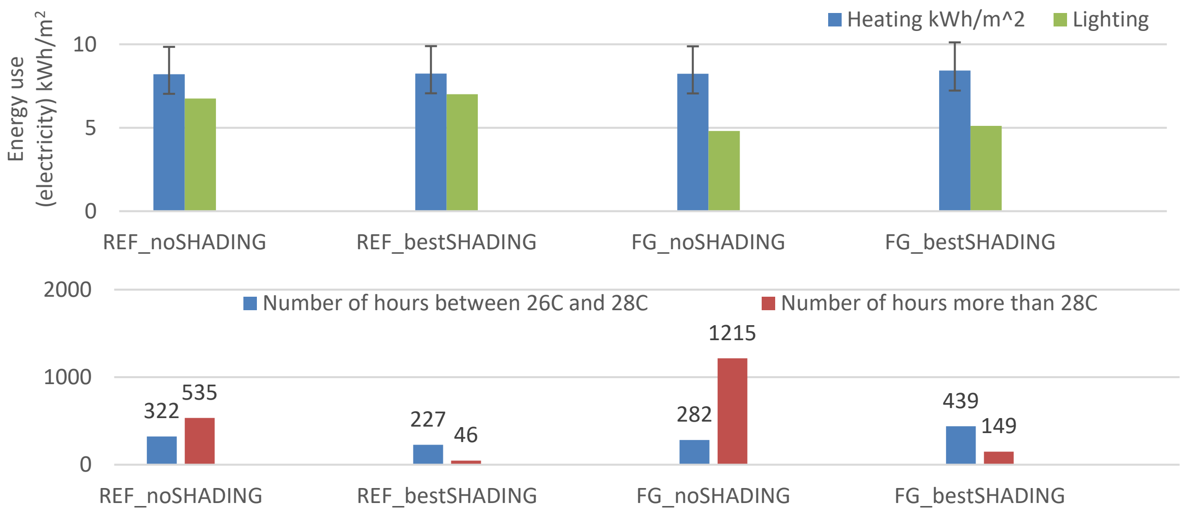

Figure 4. Energy use (top) and ODH (bottom) in the south exposed office, for the building with reference façade and curtain wall façade, in case of no mechanical cooling (2 ACH night cooling).

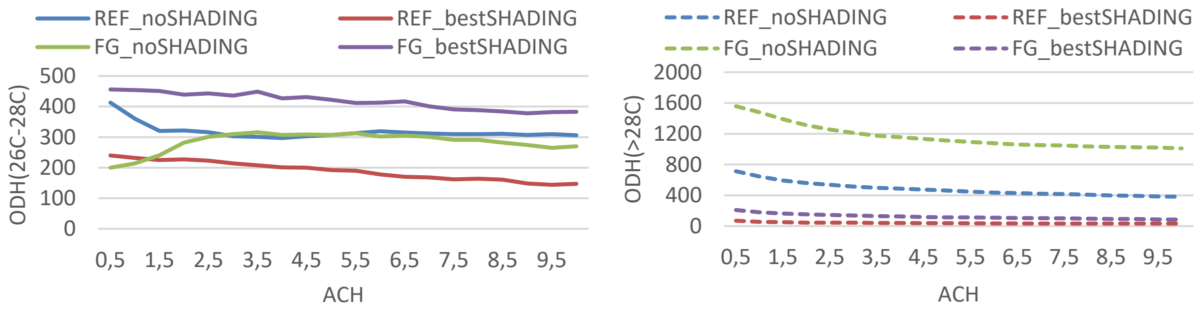

Figure 5. Overheating degree hours (ODH) for the range 26 °C to 28 °C (left) and for above 28 °C (right) as a function of air change rate in the south exposed office.

In Figure 5, the overheating degree hours between 26 °C and 28 °C, and hours above 28 °C are shown as function of ACH rate for free cooling ventilation flow, in the case of a building that only has mechanical heating systems. It can be seen that the values of ODH decrease with the increase of ACH, but not relevant changes are seen for ACH greater than 2-3 h^{-1}, especially for the cases with shading.

4. Conclusions

Fully glazed facades can be realized with current state of the art technologies in a Nordic climatic context. Integrated shading systems with suitable control logics (either based on temperature or on more advanced combinations of signals) are an important element of such constructions. If properly planned and controlled, fully glazed facades can lead to a reduced use of energy for heating, cooling, and artificial lighting, without a significant increase in the risk of discomfort due to glare.

In the case of an office building not equipped with a cooling plant, a suitable integration of passive strategies for control of indoor air temperature (free/nigh cooling) is necessary to keep the number of hours with temperature outside the comfort range within an acceptable range. An ACH rate of around 2 h^{-1} for free/night cooling seems to be a realistic target value, achievable with single side natural ventilation, or with the support of the equipment for mechanical ventilation (hybrid ventilation).

Strategies to control shading systems might change during the year to assure that the overall performance of the building is optimal. During the summer season (June to August), especially when a cooling plant is not installed, the control of solar gain should be prioritized to avoid overheating risks. With such an arrangement, highly glazed buildings without mechanical cooling can be realized in this climatic context using best available façade technologies with accurately controlled shading systems, with relatively risk of overheating leading to discomfort for the users.

Acknowledgments

This paper is part of research activities developed in the SkinTech project funded by the Research Council of Norway under grant No. 255252/E20 and the industrial partners in the project.

References

[1] Goia F 2016 *Sol. Energy* **132** 467–92.
[2] Goia F, Haase M, and Perino M 2013 *Appl Energ* **108** 515–527
[3] Grynning S, Time B, and Matusiak B 2014 *Sol Energy* **107** 182–194
[4] Georges L, Haase M, Houlihan Wiberg A, Kristjansdottir T, and Risholt B 2015 *Build Res Inf* **43** 82–93
[5] EnergyPlus – Engineering Reference, v. 8.5
[6] NS 3701:2012 - Norsk passivhusstandard for yrkesbygninger
[7] Geros V, Santamouris M, Tsangrasoulis A, and Guarracino G 1999 *Energy Build* **29** 141-154.
[8] Kolokotroni, M., & Aronis, A. 1999 *Appl energy* **63(4)** 241-253.
[9] Artmann, N., Manz, H., & Heiselberg, P. 2008 *Renewable Energy* **33(12)** 2589-2598.
[10] Ramponi, R., Angelotti, A., & Blocken, B. 2014 *Appl Energy* **123** 185-195.
[11] Handbook, Fundamentals, ASHRAE, Atlanta 2017.
[12] ASHRAE Standard 55 — Thermal environmental conditions forhuman occupancy, 2017
[13] Nabil A, Mardaljevic J 2006 *Energy Build* **38** 905–13