BENEFITS OF PASSIVE SOLAR SHADINGS IN SWEDISH CLIMATE SCENARIOS

Integrated daylight and energy study

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Master thesis in Energy-efficient and Environmental Buildings
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Lund University

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The degree project is the final part of the master programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

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Abstract

Modern well-insulated and highly glazed buildings experience increased overheating, even in cold climates. Buildings hold the biggest share of the world's energy use, and current climate crisis can exacerbate future need for cooling. The study strives to analyse passive solar shadings on a south-oriented façade, having predetermined that external and internal shadings' main function is solar heat gain and glare protection, respectively. Integrated daylight and energy study of several external shading geometries, two window sizes, and two glazing types was carried out using Radiance, Daysim, and EnergyPlus within Grasshopper, and involved preparation of daylight-driven lighting schedules, and glare-driven internal blinds schedules – further applied to annual energy simulations. Comparative nature of the study allowed to evaluate thermal and visual performance of fixed external shadings in Swedish climates, hinting that louvered overhangs may be preferable. The chief study finding highlights the gross impact of internal shading operation on overall building performance and indoor comfort. Furthermore, new climate-based performance prediction methods were developed. Those include external shading benefit index (ESBI) and internal shading benefit index (ISBI), the purpose of which is an early-design-stage recognition of critical periods in a climate year, for which a shading device ought to be foreseen, or a free cooling strategy utilised. The potential of the new tools is evident, and provided they are further developed, the methods are intended as a quick estimation of solar protection solutions, and a simulation-free blinds schedule preparation, offering eminent time-saving benefits for a design team.

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Na koniec chciałam również podziękować mojej rodzinie w Polsce za niesamowite wsparcie i nieocenioną siłę, którą mi przekazujecie i którą odczuwam na co dzień. W szczególności podziękowania za nieustanne modlitwy i dobre myśli kieruję do babci Ziuty, która wiem, że ogromnie cieszy się z naszego wspólnego sukcesu.

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Abbreviations and nomenclature

AHL – Angled Horizontal Louvers

Alt – Solar altiture /°

ASHRAE – American Society of Heating, Refrigerating and Air-Conditioning Engineers

Az – Solar azimuth /°

BS – Brise-Soleil

DBT – Dry Bulb Temperature (outdoor) /°C

DGP – Daylight Glare Probability /% or /-

DK – Denmark

DSR – Direct (normal) Solar Radiation /Wh

ESBI – External Shading Benefit Index

EUI – Energy Use Intensity /kWh

g-value (or *SGHC*) – Solar Heat Gain Coefficient

HCL – Heating Cooling Lighting

HL – Horizontal Louvers

HVAC – Heating Ventilation and Air-Conditioning

ISBI – Internal Shading Benefit Index

OH – Overhang

PV – Photovoltaic

RD – Reference Day

SE – Sweden

SMHI – Swedish Meteorological and Hydrological Institute

U-value – Thermal transmittance /W/(m²·K)

WWR – Window to Wall Ratio /%

τ_{vis} – Visual transmittance

1. Introduction

1.1 Problem motivation

The world's population, production, and energy consumption are growing, and according to International Energy Agency (IEA), the world's total energy use has doubled in the span of the last three decades (IEA, 2018). The building sector is estimated to use about 40 % of the global energy, yet, environmental and sustainable building regulations are fairly new, and the energy-efficient practices to reduce the building consumption emerged in Europe in the 1990s. Even though only around 25 % of all European buildings are non-residential, it is estimated that their average specific energy consumption per floor area is 40 % more than of the residential sector.

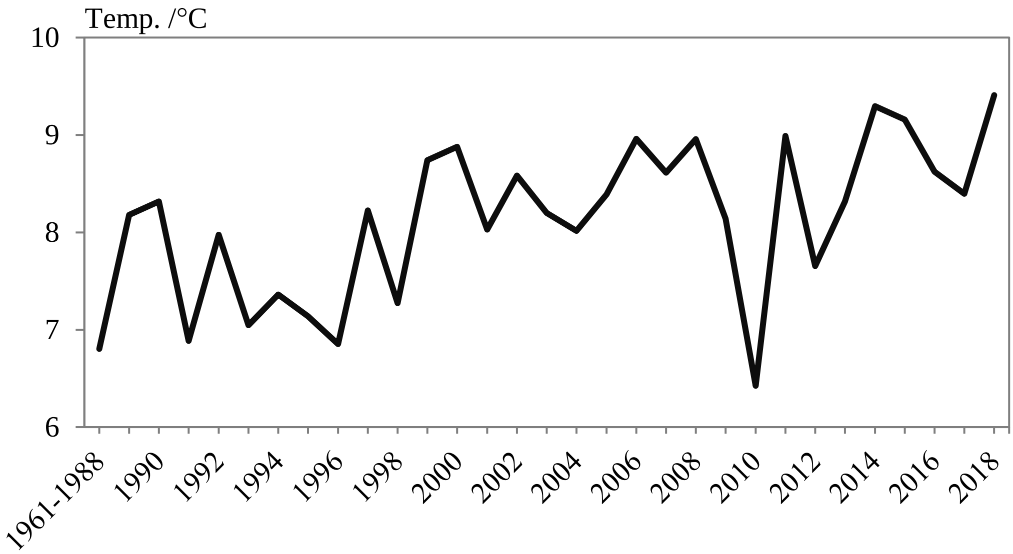


Figure 1. Annual average temperatures for Stockholm weather station no. 98210 (courtesy SMHI).

Year 2018 in Stockholm (SE) has seen the highest average temperature on record (Fig. 1, data retrieved and calculated from SMHI's open climate source). There is a scientific consensus regarding climate change, which affirms that global temperatures are rising (Cook et al., 2016). Future climate is deemed more extreme with higher occurrence of heat waves, as global temperatures are foreseen to rise by nearly 2 K by year 2050, depending on a future economic development scenario (Stockholm Resilience Centre, 2018). As global warming is advancing, planet Earth is currently about 1 K warmer than before the industrial era, and limiting the temperature rise to 2 K has become an international goal, signed upon by member states of the Paris Agreement (Horowitz, 2016). However, according to Intergovernmental Panel on Climate Change (IPCC), it is in humanity's best interest not to exceed 1.5 K warming in the aim to prevent natural disasters, extinction of species, high costs of adaptation, and human poverty (IPCC, 2018). A new study predicts that rising concentration of CO_2 in the atmosphere can also halt formation of solar-protecting stratocumulus clouds that can lower the Earth's ability to self-cool and further aggravate climate change (Schneider et al., 2019).

Norbert Lechner reminds us that “one of the main reasons for regional differences in architecture is the response to climate” (Lechner, 2014, chap. 1.2). Sustainable design ensures buildings are tailored to maximise their performance, provide good indoor climate, and abide by their local environment. Nowadays, it is a common practice to use dynamic simulations in order to predict the future performance, very often based on a statistically typical meteorological year. In the wake of global warming, however, building’s response to historically reoccurring weather events may no longer be reliable enough, and future sustainability will be challenged by climate change induced issues, such as overheating. It is known that occupants’ productivity relies upon the quality of indoor climate, which is a product of a high performance building design that ensures energy-efficiency and human comfort (Majumdar, 2019).

1.2 Goals and objectives

The study aims to tackle the problem of overheating in modern non-residential buildings in Scandinavia. Passive energy-efficient solutions were sought and tested on a south oriented reference model. The study involves shading and outdoor air cooling strategies, and consists of two main parts: i) comparative study of fenestration cases – simulating annual performance with an integrated daylight and energy approach, followed by an analysis of selected solutions, ii) performance predictions – finding new methods for climate-based estimation of passive strategies benefit, namely shadings and free cooling measures, aiming to provide predictions of annual performance. Part one compares various external fixed shading geometries against two window sizes and two types of glazing in order to identify the advantages and disadvantages of specific shading designs in Scandinavia. Local context of the study was Stockholm and Copenhagen. Part two consists of new methods estimating annual shading benefit, and aims to find influencing weather data parameters that can be used to assess the usefulness of a shading device prior to finalisation of an architectural building design. A general objective was to recognise that high cooling loads are an issue even in cold climates, and furthermore, to show the impact of lighting and internal blinds schedules on annual performance, and thus highlight the magnitude of integrated daylight and energy building assessments.

1.3 Limitations

The study does not strive to find the optimum solution but provides a comparative analysis of selected solutions. Certifications and requirements were used only as a guideline or limiting factor for comparisons. Daylight and energy simulations were carried out in one environment and were not validated by other programs, and the chosen software has provided some small limitations. Thermal comfort was considered, however, it was limited to operative temperatures and solar heat gain, without any further complex thermal comfort evaluations. It should be noted that the studied model had no surroundings and only south oriented fenestration was investigated. Selected input building parameters were meant to reflect a typical office building model in Sweden, but simultaneously, those parameters are also constraints to the overall performance. The study involves newly developed methods that have not been sufficiently validated yet, and thus should be assessed critically.

2. Background

2.1 Overheating problem

Modern buildings are seeing advancements in insulation techniques, which allowed for a significant reduction of heat loss from the building envelope. Heating demand gradually becomes a secondary issue even in traditionally heating dominated climates (Grynning et al., 2014). Reduction of infiltration, lower U-values, highly glazed facades, and high internal heat loads of modern office buildings all contribute to overheating and by extension cooling loads higher than in conventional 'leaky' buildings. Swedish building regulations (BBR, 2016, sec. 9:5) state that "the need for cooling shall be minimised through design and technical measures". The importance of solar protection devices in reducing cooling loads, ensuring thermal comfort, and mitigating glare in a Swedish cold climate scenario was demonstrated by Wall and Bülow-Hübe (2003). Proposed Norwegian energy-efficient design guidelines mention cooling mitigation strategies that consist of: i) 'prevent' – solar protection i.e. shading systems, ii) 'modulate' – addition of thermal mass, iii) 'utilise' – use of natural ventilation (Haase et al., 2011). It should be noted that prevention is the first fundamental tier of the above cooling reduction strategies. Furthermore, ASHRAE Handbook Fundamentals (2017, p. 15.33) reads that "the most effective way to reduce the solar load on fenestration is to intercept direct radiation from the sun before it reaches the glazing system".

Researchers are in agreement that fenestration design must incorporate solar shading solutions in early building design stages, as it will have an immense effect on energy reduction and improvement of indoor comfort. Poirazis, Blomsterberg, and Wall (2008) in their study on Swedish office buildings emphasise the gravity of 'careful design', which is particularly necessary in case of highly glazed facades, and must be supported by thermal simulations. The key functions of windows, which are daylighting and visual contact with the outdoors should be preserved. It is known that glass allows short wavelength solar radiation to pass through and heat up the interior surfaces, which consequently radiate long infrared waves that the glass is impervious to, so the heat stays trapped inside the zone. It is a commonly observed phenomenon in greenhouses and highly glazed buildings. Building orientation, size, location, shading by surroundings, and room distribution belong to design prerequisites that should be considered for increased energy efficiency. However, limitations of building plot characteristics might leave critical building zones exposed to higher insolation and, in that case particularly, solar protection is vital.

Reinhart and Wienold (2011) pointed out that daylight simulations are used reluctantly within the building design community due to long simulation time and complexity of the simulation process and available software. They intended to help designers to interpret and present the outcome of their simulations by introducing 'daylighting dashboard'. The tool combines daylight, comfort, and energy metrics to show design performance in a practical, easy-to-compare form, and the authors encourage the use of such presentation methods to promote integrated daylight and energy simulations in the building industry. Bueno et al. (2015) developed a new modelling method for fenestration systems – 'Fener', which is meant to speed up the simulation process as it allows for daylight and energy to be simulated simultaneously. Advances in simulation techniques are on their way, nonetheless, it is crucial for architects and building engineers to recognise the need for integrated approach today, from the early stages of design process. As many studies have shown, this approach can provide high quality of indoor comfort alongside reduced energy use.

2.2 Solar shadings

History of architecture holds numerous examples of fixed shading elements as an integral part of a building providing solar protection inside as well as outside and oftentimes adding signature architectural features (Lechner, 2014, chap. 9.1). Modern architecture, due to technological advancements, offers many more options to choose from, when it comes to solar protection, like special glass materials, however, as it was mentioned in the previous section, the best results can be achieved when solar rays are prevented from falling onto glazing. A study of external solar shadings in Jordan found an optimal geometry that provides good daylighting conditions while successfully reducing solar heat gain (Alzoubi and Al-Zoubi, 2010) but the optimisation has to be customised for a specific climate (Dubois, 1997). Some architects in Scandinavia were unaware that shadings should be incorporated into a building design and how impactful such a design choice would be on building energy use (Kanters et al., 2013). Solar shading devices can be placed externally or internally. Similarly, devices can be fixed or movable, and, in case of the latter, manually or automatically controlled.

Externally placed solar shading is more effective in solar heat gain prevention than internal devices (Poirazis et al., 2008). According to AHSRAE (2017) external shadings as fixed elements have higher life expectancy and are less prone to degradation, as opposed to movable ones that can entail energy use for operation, higher initial and running costs, and an increased risk of breakage. Movable shading elements also need frequent maintenance and a designated control strategy, which can be linked to a number of issues. If movable devices are employed manually, the responsibility of correctly executed adjustments lies on occupants or building management, which adds human factor into the system performance and can potentially reduce the efficiency thereof. Whereas automated control systems rely on setpoints, sensors, periodic inspections, and most importantly, they can no longer be called 'passive' as they run on electricity. Automated shading control is further discussed in section 2.3. On the other hand, fixed shadings permanently block a portion of natural daylight, which may cause increased use of electric lights. At the same time though, shading elements can provide a placement opportunity for building integration of an active solar system such as photovoltaics (PV) and the energy production potential is evident (Mandalaki et al., 2012).

While internal shading is worse in reducing solar heat gain as it absorbs solar radiation and emits it within the room, it is often required to supplement for external shading in order to satisfy other comfort related functions such as: radiant energy protection, privacy, brightness control (ASHRAE, 2017). Two of the functions are associated with low solar angles, very common in higher latitudes, which are difficult to shade, especially with fixed shadings, and it is when internal shading devices come in most useful. Periodical necessity for employment of internal blinds means they are predominantly movable and require a control strategy.

There are various performance metrics that can help assess the effectiveness of a shading device, examples of which were listed and include:

- Cooling energy,
- Energy use intensity (EUI),

- Peak loads,
- Solar gain,
- Glare,
- Daylight (distribution, useful daylight, autonomy, etc.),
- Thermal comfort.

The above metrics can be useful for comparison and further selection of a shading design, however, simulations require technical knowledge of oftentimes complex programs, and the process is time-consuming. An informed decision regarding final fenestration design would often rely upon results of above design metrics, which are affected by many building-specific parameters e.g. WWR, building geometry, HVAC, internal loads, and surroundings.

2.3 Occupant control

While building physics, a cornerstone science for energy performance assessment, has been widely studied and is now an inherent part of a sustainable building design, human factor within buildings that is the occupant behaviour remains inscrutable. Increasing number of studies on the subject have been published in recent years, but there is no clear consensus about the patterns in which people respond to the indoor climate conditions (Zhang et al., 2018). The impact of occupant behaviour on building performance has been widely recognised, and it was noted that the simulated energy use can differ as much as three times when compared to the actual performance (Delzendeh et al., 2017). Therefore, the energy and daylight simulations should consider user control patterns as they will affect the overall results (Van Den Wymelenberg, 2012). The subject of human interactions is very complex and dependant on location, cultural inclinations, and acceptable comfort levels that are understandably subjective and personal.

In modern buildings, systems such as electric lights, internal shading, thermostat, etc. can respond to manual and/or automated control. Among many findings on the subject of occupant control behaviour, a field study by Sadeghi et al. (2016) suggests that occupants express higher satisfaction with the indoor climate when they are free to adjust the control levels to their liking. It was also found that easily accessible light switch panels encourage more occupant interaction, which may lead to energy savings and better utilisation of daylight in the zone. The study underlined the importance of prediction regarding the behaviour patterns, and pointed out the interdependency of internal blinds and lighting control that should be accounted for.

Efforts were made to understand and predict occupant behaviour. Reinhart (2004) developed a probabilistic algorithm based model of lighting control – Lightswitch-2002 that aims to mimic the occupant behaviour using scenarios of passive and active user behaviours. It processes results obtained from annual daylight simulation to produce a lighting schedule that can be input to an energy simulation. In a separate study, three types of occupant behaviour were identified by Bavaresco and Ghisi (2018): two passive – leaving blinds drawn or retracted, and one active. It was found that having internal blinds more frequently open rather than closed allowed higher energy savings. When occupants are given complete control over the blinds state, by which they also decide whether they have a view, they tend to retract the blind more frequently that indicates strong preference for the outdoor view (Sanati and Utzinger, 2013). Moreover, occupants are willing to tolerate some degree of discomfort i.e.

glare in exchange for view to the outside (Karlsen et al., 2016). This shows potential for energy savings, provided that the fenestration and control mechanism are designed for occupants comfort and allow for individual adjustments. Scandinavian architects interviewed by Kanters (2013) expressed their scepticism towards computer operated systems because they share a conviction that the occupants should be able to decide on their working conditions.

Various control types and thresholds of internal blinds operation can be found in literature (Van Den Wymelenberg, 2012). A commonly used control measure variable is illuminance since internal blinds are closely associated with visual comfort rather than thermal comfort. The reason might be that in reality thermal comfort is harder to evaluate, measure, and also to sense by an occupant, since in a conditioned space the occupant might not be aware of excessive solar gain. Illuminance can be expressed simply in lux on a surface or in terms of glare. Daylight glare probability (DGP) is a method of calculating the likelihood of glare occurrence by analysing illuminances at occupant's eye level. It is a way of predicting visual discomfort caused by extreme brightness or contrasts within a field of view (Wienold and Christoffersen, 2006). DGP is expressed as percentage and values above 40 % are expected to cause disturbing glare that might trigger an occupant to engage blinds. Internal blinds schedule can therefore be driven by DGP (Reinhart et al., 2013) and this control method was found to be most accurately representing the average control behaviour in a study by da Silva, Leal and Andersen (2012) comparing different control types and thresholds.

Control strategies either help mimic control behaviour in simulated manually operated systems or be employed to operate a dynamic system. There is a future potential alongside drawbacks in automated dynamic facades as they exhibit higher reliability and energy savings (Bakker et al., 2014). Many studies debate occupant preferences regarding manual control and dissatisfaction with automated systems. Bakker et al. have concluded that the feedback on dynamic facades can be positive provided that the transitions are infrequent and subtle. Other drawbacks often involve economy – higher initial and running costs, and maintenance – higher risk of failure with moveable parts (Nielsen et al., 2011). Study of dynamic facades in Abu Dhabi (Hammad and Abu-Hijleh, 2010) suggests that the added cost and effort that comes with dynamic shadings might not be justified.

2.4 Free cooling

Passive cooling strategies are sought for to replace or support a conventional mechanical air-conditioning system in order to achieve substantial energy savings. The alternative cooling methods utilise various natural sinks to dissipate heat, such as ground, sky, air, and water (Samuel et al., 2013). Natural ventilation by means of e.g. cross ventilation through fenestration openings can be considered, however, ASHRAE (2017, p. 16.2) warns against negative consequences of natural ventilation in commercial buildings, as, depending on local conditions, it can threaten building security, affect indoor comfort, and introduce air pollutants. Mechanical ventilation is then more reliable in providing clean supply of fresh air with predetermined flow rates, nonetheless, it is an active system. In Sweden, the building law inflicts strict ventilation rules and requires a constant exchange of air at a certain rate per floor area, which can be guaranteed by a mechanical system (BBR, 2016). One way to make cooling with a mechanical system more energy-efficient is the addition of an air-side economiser, which automatically increases the outdoor airflow through the system in case there is a cooling load and the temperature outside is lower than the temperature of the exhaust air. It is a preferable solution for commercial buildings over natural ventilation according to ASHRAE.

Combining mechanical ventilation with natural ventilation practices by means of a hybrid system was found to work very well in a number of climates in reducing energy while maintaining indoor comfort (Emmerich, 2006). Air-side economisers are especially recommended for reduction of cooling loads in moderate to cold climates and for buildings with high internal gains, such as office spaces, although, humidity issues connected to increased airflow must be resolved (ASHRAE, 2017, p. 16.20). The use of night-time natural ventilation in office building can be advantageous in Sweden for two reasons: summer nights in Scandinavia provide colder air temperatures, and the building law is less strict about ventilation rates outside of occupancy time. Studies show potential of night ventilation in reducing cooling loads for it can flush out heat accumulated in the building over a day and cool internal building mass to avoid overheating the following day. Liu, Wittchen, and Heiselberg (2015) developed an algorithm for automated control of night ventilation for office buildings in Denmark, and showed its benefits on building thermal performance.

Interestingly, shading geometry can affect the way air passes through a building in a natural ventilation process. Lechner (2014, chap. 10.6) identified that a solid overhang is better for night-time cooling as, due to pressurisation on sides of the overhang, air passing through a building is curved upwards, therefore, cools down the thermal mass more effectively. Whereas, a louvered overhang (or brise-soleil) might work better with daytime natural ventilation strategy as the air stream is horizontal.

2.5 Integrated daylight and energy approach

Climate based dynamic simulation tools are widely used in today's design process and performance evaluations (Kirimtat et al., 2016). Increasing number of studies underline the importance of an integrated daylight and energy performance analysis in a holistic approach that considers interdependency of visual and thermal dynamics in a building. A fundamental correlation between daylight and energy is the use of electric lights. Especially that the trends in architecture favour large windows that should admit plenty of daylight and consequently save electricity on lighting. Manzan (2014) tested external fixed shadings for Italian climates and concluded that solar protection design should never neglect the inevitable impact of shadings on electric lighting use. Since every lighting source emits heat, not only does daylighting impact the electrical energy use to power lights but also the demand for heating and cooling. Tzempelikos and Athienitis (2007) carried out an in-depth study of the interdependence od daylight and energy by analysing a range of window-to-wall ratios (WWR). They compared passive and active lighting and shading control methods and by comparing the annual energy use demonstrated significance of an integrated approach in building design.

More recent studies put emphasis on visual comfort in addition to thermal performance of buildings. State-of-the-art study on advanced shading systems listed a set of relevant criteria that can be used to make an informed design of a fenestration system (Kuhn, 2017). Those included solar heat gain reduction, thermal comfort, daylighting, visual comfort, amongst other aesthetic and environmental criteria. Karlsen et al. (2016) tackled the issue of control strategies of external and internal shading devices in order to optimise the design for minimum glare with maximum daylighting and view to the outside. The latter is a commonly used indicator of quality and visual comfort of a space, as internal blinds operation would obstruct the view to the outside. Satisfaction with the indoor environment is linked to higher productivity and well-being of occupants. Those who experience glare work less efficiently and can report headaches, but on the other hand, those who occupy workstations next to the perimeter tend to express higher satisfaction as they have more access to daylight (Day et al., 2019).

3. Methodology

3.1 Simulation setup

3.1.1 Computer tools

The study is of theoretical nature and aims to assess expected future annual energy and daylighting building performance, thus relies on use of computer programs. 3D-modelling was done in Rhinoceros 5 and Grasshopper, which is an algorithmic modelling tool that is integrated with Rhino. Grasshopper was also used for basic data-handling and mathematical operations on annual data sets. Additionally, MS Excel was used for data analysis. Climate properties were read from an EnergyPlus Weather file (*epw file format), which represents a typical meteorological year, based on multiple years of historical data recorded at a given local weather station.

Both energy and daylight simulations, as well as climate analysis, were conducted in Grasshopper environment with the use of free open-source Ladybug tools (Honeybee, Ladybug, and Dragonfly). Thereon, annual climate-based simulations were computed through EnergyPlus – energy and thermal comfort, Radiance and Daysim – daylight and visual comfort.

3.1.2 Model and climate

The study was conducted on a theoretical typical office building room, often referred to by researchers as a shoebox model. The geometry was borrowed from a standardized modelling method for integrated daylight and energy simulations, which was proposed by Reinhart, Jakubiec and Ibarra (2013). The reference model, as it was referred to by the authors, has internal dimensions of 3.6 m × 8.2 m × 2.8 m. There are no surrounding objects to shade the building. Surface boundary conditions are adiabatic, except for one external wall on which a window is placed (Fig. 2). Two window-to-wall ratio (WWR) studied cases were 44 %, which constitutes a regular window size, and 84 % that refers to a highly glazed façade. WWR was measured against the internal wall dimensions, and does not include frames. The windows were placed centrally on the external wall. The prime orientation of the model is due south. Two climate scenarios were tested. The first one - Copenhagen (DK) represents both the region of southwest of Sweden (Skåne) and east of Denmark, the second one, representing the eastern central part of Sweden, is Stockholm (SE). Located in Scandinavia, the two climate scenarios can be both characterised as cold with long daylight days in summer, short in winter, and rather low solar angles. Stockholm is colder and sunnier than Copenhagen, it is also more northern.

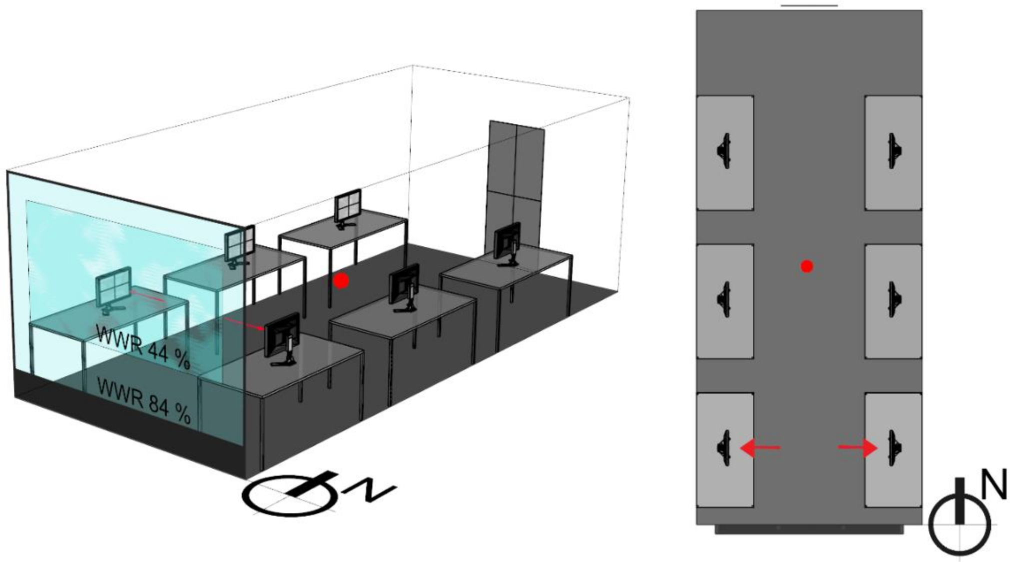


Figure 2. Perspective (on the left) and top (on the right) view of the reference model.

3.1.3 Thermal zones

In the original reference model, the room was split into two thermal zones in ratio 2:1 (larger one includes the window), which had separate lighting controls with schedules that governed their operation. It was done having in mind that the room geometry is deep and thus daylight will struggle to reach the rear end. In this study, however, the room was considered as one thermal zone. The differences between a single and a two-zone model were investigated further as one of the 'side studies'. The study was carried out in order to find how sensitive the results are depending on selected zone modelling method. The importance of working with a lighting schedule is that lighting load as a part of internal gains is affecting the heating and cooling demand (illustrated in Fig. 4).

3.1.4 Building components and HVAC

Properties of building envelope components are listed in Table 1. The external wall construction was based on an exemplary typical Swedish lightweight wall as depicted by Janson (2010, p. 64). The internal walls are lightweight. The interior floor and ceiling construction was taken from the EnergyPlus library, available within Honeybee 0.0.64, and consists of 6 mm acoustic tile, an air gap, and 100 mm lightweight concrete.

Table 1. Building components parameters.

	Reflectance; Other parameters
External wall	35 %; U-value = 0.13 W/(m²·K), Air leakage (@50 Pa) < 6 l/s/m²
Floor	20 %; Thermal capacity = 107.5 kJ/K/m²
Ceiling	80 %
Internal walls	50 %; Lightweight, Thermal capacity = 16.6 kJ/K/m²
External ground	20 %; Modelled as an upside down sky hemisphere (Radiance default)

Two window solutions were tested, their properties listed in Table 2. The windows are triple-glazed, argon-filled.

Table 2. Glazing types and properties.

	Product name	U-value /(W/m²/K)	g-value (SGHC)	τ_{vis}
Clear glass	iplus top 3	0.6	0.5	0.7
Selective glass	ipasol Ultraselect	0.5	0.26	0.54

The building is supplied with constant air volume outdoor air flow of 0.35 l/s per square meter of floor area as is recommended in the Swedish building code (BBR, 2016) with additional 7 l/s per person that meets a bronze criterion of Swedish Miljöbyggnad standard (SGBC, 2017). The system is equipped with a heat exchanger – enthalpy wheel with sensible heat recovery efficiency of 81 %. Zone conditioning is done with a default EnergyPlus HVAC system called 'Ideal Air Loads'. With this system, all the heating and cooling is airborne so the air alone has to meet the zone thermal thresholds. Specific detailed HVAC system was not designed.

Scandinavian countries are characterised by a rather cold climate, therefore, an outdoor air cooling strategy (described in section 2.4) was additionally investigated. Since Swedish regulations are strict about the quality and quantity of supply air thus buildings often require a mechanical system, it was proposed that the outdoor air cooling strategy involves an air-side economiser as an addition to an already existing air system. The economiser works on a differential dry bulb temperature basis and would increase the outdoor air flow through the system in case there was a cooling need and the outdoor air temperature was higher than the exhaust air temperature. Cooling energy need was then compared for scenarios with and without an air-side economiser, however, the impact on thermal comfort by potential cold draughts or increased energy use of the mechanical fans were not examined.

3.1.5 Occupancy, loads, and schedules

There are six workstations available within the space of the reference model (Fig. 2) but the permanent occupancy is set to 4 persons with heat generation of 120 W/person, which according to ASHRAE (2017, p. 9.6) is equivalent to an average adult performing an office activity somewhere between typing and filing while seated. The occupancy time is 8AM to 6PM, seven days a week, with summer daylight saving time from April to October, as it was in the original reference model. The equipment load is set to 8 W/m², and the schedule follows the occupancy patterns. Heating setpoint (target air temperature during occupancy) and setback (allowed air temperature outside of occupancy) were 21 °C and 15 °C respectively, and analogously, 25 °C and 30 °C for cooling.

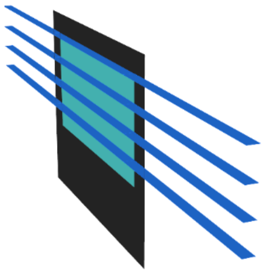
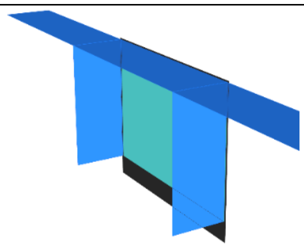
The lighting load was obtained with Honeybee 0.0.64 Lighting Density Calculator component using default luminous efficacy for fluorescent T5 tubes, medium maintenance factor, and light illuminance level of 300 lux. The resulting lighting density was 6.9 W/m². The selected work plane illuminance threshold of 300 lux is frequently found in recent literature and requirements (BREEAM-SE, 2017; LEED, 2019) as opposed to typical 500 lux threshold. The shift towards a lower lighting level for an office is driven by a technological shift from paper to computer based office work (Richman, 2012).

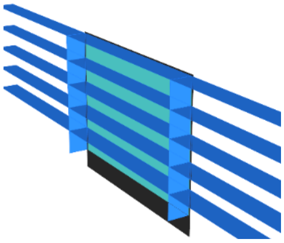
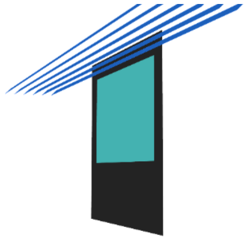
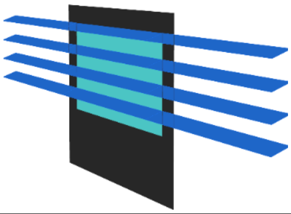
The operation of electric lights is controlled with a manual on/off switch without dimming. Custom schedules, as they will be called from now on, are prepared using information about the illuminance level from Radiance annual daylight simulation. Sensor point was placed in the centre of the zone at 0.8 m above the floor. The control can be perceived as automated rather than occupant controlled, as it does not account for real life user's behaviour patterns and reaction time. This manual control type can therefore be called "active", as it is assumed that the user will react to the changing conditions without failure. Even though the method does not reflect realistic user patterns, it is straightforward and allows for further comparison of shading solutions and other parameters. The purpose of this study was not to determine the range of possible results by applying multiple user behaviour scenarios, but to use a fixed pattern repeatedly in order to assess the impacts of solution and compare them. With the predictable kind of control system, which is free of human factor, the resulting schedule can serve as a daylight metric to describe the daylighting environment of the zone. Percentage of occupancy time when the lights are switched on is thereby an indicator of daylight utilisation.

3.1.6 External shading cases

External fixed shading cases were designed for the south oriented façade, and the selection of solutions can be found in Table 3.

Table 3. External shading cases.

NAME	RENDER	DIMENSIONS
Overhang (OH) *Render: OH60*		**Offset:** - WWR 44 %: (60, 120) cm - WWR 84 %: (100, 200) cm
Horizontal louvers (HL) *Render: 4 HL15*		**Offset:** - WWR 44 %: (15, 30) cm - WWR 84 %: (20, 40) cm **Number:** - WWR 44 %: 4 louvers - WWR 84 %: 5 louvers
Overhang with vertical fins (OH + V) *Render: OH100+V100*		Study case for WWR 84 %: OH 100 cm + V 100 cm

Horizontal louvers with vertical fins (HL + V) *Render: HL40+V40*		Study case for WWR 84%: HL 40 cm + V 40 cm
Brise-soleil or louvered overhang (BS) *Render: BS120*		**Offset:** - WWR 44 %: (60, 120) cm - WWR 84 %: (100, 200) cm **Number:** - WWR 44 %: (3, 6) louvers - WWR 84 %: (5, 10) louvers **Angle:** 45°
Angled horizontal louvers (AHL) *Render: 4 AHL30*		**Offset:** - WWR 44 %: (15, 30) cm - WWR 84 %: (20, 40) cm **Number:** - WWR 44 %: 4 louvers - WWR 84 %: 5 louvers **Angle:** 20°

The first step of designing external shading was to analyse the solar gain and isolate solar vectors from the weather file that are concurrent with high solar heat gain in the zone. For this purpose, Swedish Miljöbyggnad certification provided solar heat gain thresholds that set a limit for the amount of solar gain per floor area that can occur at any given hour of the summer season – Equinox to Equinox (SGBC, 2017, p. 11). Three levels of solar heat avoidance design quality in Miljöbyggnad are bronze, silver and gold, each with a criterion of maximum solar gain of (40, 32, 22) W/m² respectively for a newly built construction. Specific solar vectors for the hours of the year when solar gain was above a chosen threshold and concurrent high outdoor temperature (above 17 °C) were isolated and further input into Ladybug 0.0.67 Shading Designer component, which outputs a shading geometry to block all input solar vectors from falling onto glazed parts. The results of this preliminary study helped develop study shading cases.

Two main fixed external shading design concepts for south orientation prevail in literature and case studies: overhang and multiple horizontal louvers, and those are the main types of shadings under analysis. Two sizes of each shading type were selected, so that the shading offset corresponds to roughly 40 % and 80 % of the window height. The dimensions can be found in Table 3. Overhang and corresponding size of horizontal louvers shading are both horizontal elements that have the same total length of the shading elements, the latter is simply divided into smaller sections (e.g. OH: 100 cm = HL: 5 × 20 cm).

Brise-soleil is a horizontal element above glazing deflecting solar radiation in a similar way to an overhang, but as opposed to one, it is made of multiple spaced angled louvers that allow air, precipitation, and light to pass through. The angle of the slats was set to 45° as a design choice. Thereafter, the spacing was set to 0.2 m, and the slat width that was necessary to shade direct sunrays was calculated for the highest solar angle at summer solstice. The total horizontal offset of the brise-soleil was the same as for the overhangs, however, the resulting total added brise-soleil louvers length was 19 % less than of the overhang, which means less material can be used with brise-soleil type of solar shading.

The effect of tilting of the horizontal louvers was also investigated. The angle of rotation was 20°. The angled horizontal louvers obstruct view to the outside when looking perpendicularly though the window, as opposed to the initial louvers design. The geometrical loss of outdoor view for the larger louvers size is 15 % (for WWR 84 %) to 27 % (for WWR 44 %) of the window surface area with view position normal to the surface. However, the angled shading geometry provides a less obstructed view downwards, which might be preferable in case of a multi-storey building as it ensures view down to the street level.

Vertical fins have been added to two of the external shading cases to check whether they can be beneficial for a south oriented fenestration. The addition comprises of two vertical elements, one on each side of the glazing.

All fixed external shading geometries have 20 % diffuse-only reflectance for both visual light part of the spectrum in daylight simulations and for the non-visible thermal parts. The reflectance of 20 % is a default context objects reflectance setting in EnergyPlus and Radiance. Since the shading material was assigned a rather low reflectance value, a reflectance sensitivity analysis was conducted as a ‘side study’. Shading reflectances of (20, 50, 80) % were investigated on a large window with a large horizontal louver shading geometry (5 HL40). The reason is that the bigger the surface, the more pronounced the effect of higher reflectance that should be observed. The study was done for Stockholm climate and WWR 84 %. Electric lights use was compared using the same 300 lux threshold custom lighting schedule.

3.1.7 Internal blinds

While external shading device is used primarily to deflect the sunrays in order to protect the space from overheating, it can simultaneously provide a better visual comfort for the occupants by lowering the irradiance of the internal surfaces. The effect on the visual aspect of the indoor environment was evaluated through annual glare simulations with Daysim and Radiance by Honeybee. Internal blinds were used as a complementary manually operated shading device that was to be active only in occurrence of disturbing glare (DGP > 0.4). Thus, the control model is similar to the previously explained lighting control method.

The office model was simulated for DGP (Daylight Glare Probability) on the eye level of a seated occupant just like in the original reference model - 1.18 m above the floor. The occupant is seated in the nearest work station from the window, facing their computer screen placed against east or west side wall (Reinhart et al., 2013), (Fig. 2). The schedules were created using a DGP threshold of 40 %, above which occupants may experience disturbing glare. Only the nearest to the window working stations were analysed as they will experience high illuminance of the surroundings, and furthermore, it is most likely that the blinds will be operated by occupants sitting closest to the control mechanism. Visual discomfort is therefore the driver of manual blinds control. This method is straightforwardly based on probability of glare occurrence, which could mimic behaviour of an active occupant, but may not reflect real life occupant control patterns, and does not account for passive user scenarios. It should be noted that visual comfort is also subject to personal perception and sensitivity to light. The schedule provides that when DGP above threshold, the blinds are down. Schedules based on DGP results for west and east facing occupant were merged to create one schedule for the zone. DGP driven blinds control strategy allows to classify performance of fenestration designs through measure of occupancy time when the occupants have a view to the outside, which simultaneously translates to annual frequency of glare-free environment that the external shading alone provides.

Considering manual control methods for internal blinds, glare driven operation might be more realistic than a thermal load or radiation based model, as the occupant in an air-conditioned space with air temperature within comfort limits would perhaps fail to notice thermal discomfort regarding solar irradiation. The occupant would be much more likely to react upon a changing visual scene as the office work and productivity is highly dependent on undisrupted visual perception.

PET fabric was chosen as the internal blinds material. The fabric is made from recycled plastic waste with emissivity of 0.78 (Zhang et al., 2009), medium transmittance of 0.1 (Atzeri et al., 2014), and reflectance of 0.12 in a shade of white. When the blinds are down, the electric lights have to be switched on, as the blinds do not allow enough daylight to meet the lighting control illuminance threshold, but can reduce the glare probability to an acceptable non-disturbing level.

3.2 Annual performance

Shading designs were assessed with a holistic approach that involves integrated daylight and energy simulations. Annual daylight simulations were carried out using Radiance, while annual glare as DGP was achieved with Daysim simulation engine, which is Radiance-based. Thermal modelling and energy simulations were performed in EnergyPlus engine. The geometries were modelled in Rhinoceros and Grasshopper, and the simulation setup was handled in Grasshopper environment using Ladybug and Honeybee tools. The chart in Figure 3 illustrates the workflow method applied in this study. Daylight and glare simulations are performed separately and could in theory be ran in parallel, if the software environment allowed. The principles of obtaining the lighting schedules were explained in section 3.1.4, while the method of internal blinds DGP-driven schedules was described in section 3.1.6. Seeing from the chart in Figure 3, two types of results can be obtained: with and without internal blinds employment. When internal blinds are considered, daylight based lighting schedules have to be altered to include electric lighting operation when blinds are drawn. Energy simulation is always the last step of the simulation workflow.

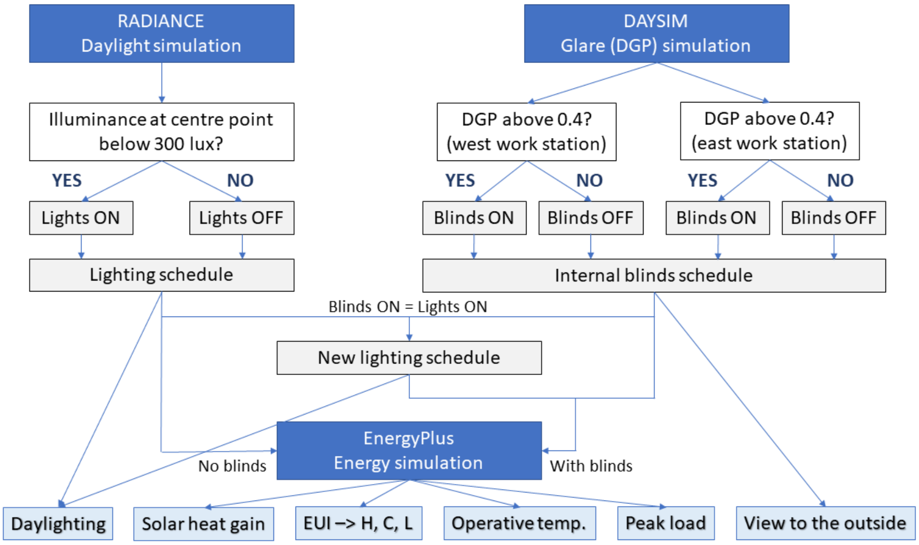


Figure 3. Workflow and method for annual performance evaluation.

At the very bottom of Figure 3, outputs of the study were collected, which ultimately constitute design metrics driving the evaluation of design performance. Two main groups of metrics can be identified: i) daylight and visual comfort, ii) energy and thermal comfort.

3.2.1 Daylight and visual comfort

Daylighting in literature is described and quantified in many different ways. In this study, daylight illuminance at the centre point of the zone (marked in Fig. 2) is the determinant for electric lighting schedule, as previously described in 3.1.5. Therefore, to describe zone daylighting, electric lights operation duration was used as a quantifying variable, expressed as a percentage of yearly occupancy time when electric lights are on. A reverse of that would be the occupancy time when daylight is a sufficient lighting source. As daylight simulations are time-consuming, the quality of simulations was set to low, except for a greater number of ambient bounces (Table 4). Impact of higher quality simulation parameters on daylighting results was investigated in a ‘side study’. It was checked whether a higher quality of daylight simulations would have a significant impact on the lighting use with BS200 compared with OH200 on clear glass WWR 84 % in Stockholm. Louvered geometry of brise-soleil is expected to bring more daylight to the space than the overhang. The quality setting was raised to medium and the number of ambient bounces increased to 5.

Table 4. Daylight simulation quality parameters.

ambient bounces	4
ambient division	512 (1024 in glare sim.)
ambient sampling	128
ambient resolution	16
ambient accuracy	0.25

Visual comfort is not exactly a design metric, due to the fact that the visual comfort is ensured with the use of internal blinds. One can compare two cases – with and without internal blinds, to see how many hours of glare discomfort and occupant can experience without internal shading. However, glare issue cannot be quantified in the case where internal blinds are installed because it is simply eliminated. Instead, a measure of the availability of the view to the outside, as naturally when the blinds are down, the occupant is deprived of the outdoor view. The view to the outside metric is therefore reflecting on the quality of the space, in which glare issues had been dealt with and a visually comfortable environment provisioned. Blinds operation affect yet another above mentioned metric, which is the use of electric lights, as when the blinds are drawn electric lights have to meet the lighting level.

3.2.2 Energy and thermal comfort

Energy is primarily presented as annual energy use intensity (EUI) that includes heating, cooling, and lighting (HCL). Driven by daylight simulations, lighting is also affecting zone cooling and heating because it emits heat into the zone when lights are on (Fig. 7). Therefore, any modification to window fenestration design that changes daylighting conditions would by extension have a significant impact on the cooling and heating loads. For this reason, it is important that buildings are studied holistically, taking into account daylight and energy as integral parts that affect one another.

Solar heat gain criterion is included in chapter 2 of Swedish Green Building Certification Miljöbyggnad 3.0 (2017). The purpose is to avoid direct transmission of solar rays causing overheating and to minimise the system size, which means that the criterion tackles thermal comfort together with technical and economic aspects of a cooling system. Threshold of gold standard was chosen to compare the shading solutions in terms of the number of hours with solar heat gain higher than 22 W/m^2.

Since solar radiation comprises of thermal and visual spectrum ranges, there is a correlation between reduction of solar heat gain and increased lighting heat gain as daylight levels are concurrently reduced (Fig. 4). Both thermal and daylighting effects of sun depend on WWR, and additionally, thermal and visual window properties are expressed by solar heat gain coefficient (g-value) and visual transmittance (τ_{vis}) respectively. How much of consumed lighting power turns into heat will depend of the lighting source’s luminous efficacy. The phenomenon was investigated in order to check what part of the reduced under Miljöbyggnad threshold solar gain hours does not receive enough daylight that the lights should be switched on. The ‘side study’ is aiming to find whether reduction in solar gain is ‘exchanged’ for increase in lighting heat gain.

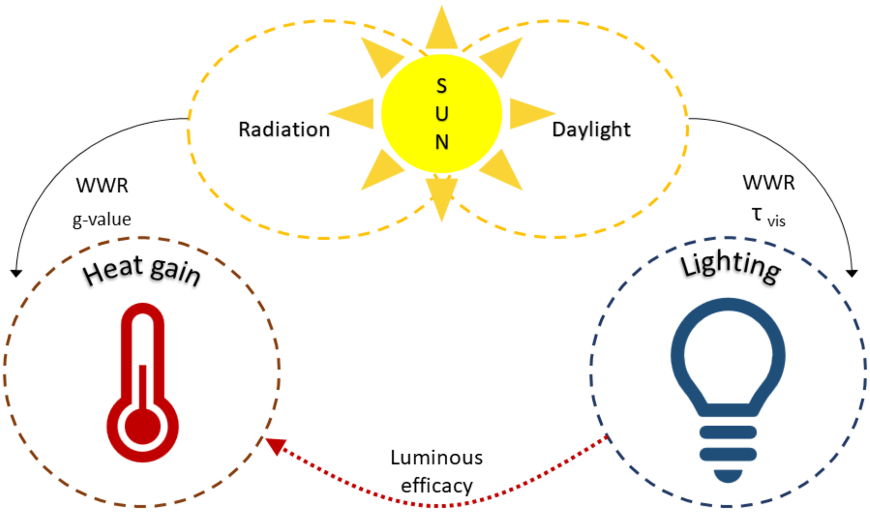


Figure 4. Relations between the sun, lighting, and internal heat gain.

Similarly to solar heat gain, peak load results can indicate which fenestration design would require a smaller cooling system. However, because in this study a cooling system was not designed, the peak load values should only be used for comparison between the solutions and not at a face value.

Thermal comfort is a complex and subjective issue that can be evaluated using known indicators of thermal comfort, but a rather simple evaluation can be done with information about operative temperatures. When operative temperature is outside of the air temperature setpoint range during occupancy time, it can be presumed that occupants might experience thermal discomfort. The main focus is the cooling issue, thus, it was checked for what part of the occupancy time in a year the zone would record operative temperatures higher than the setpoint of 25 °C. Additionally, following BBR requirements for workspaces (2016), it was checked whether a heating setback of 15 °C can cause the morning operative temperatures to drop below 18 °C, as it is advised against in the BBR. As previously mentioned, measure of solar heat gain is also a thermal comfort control method.

3.3 Performance prediction methods

3.3.1 Reference days

Reference days (RDs) were used in order to analyse the climate data and grasp its impact on the energy use and indoor climate of a building geometry. Selection of reference days was based on:

- Climate day type (five types as seen in Figure 5),
- Solar angle (or altitude).

A method of categorising days in an annual weather file into climate day types is proposed. The method takes local parameters of the weather file, which are i) direct normal solar radiation (DSR) total for a day expressed in Wh/m², ii) maximum dry bulb temperature (DBT.max) for a day in °C. For the two data sets, median and quartile values are determined, as can be seen in box plots in Figure 5. Since day types are based on climate specific values, the limiting values will be different for every other climate file. Table 5 presents the suggested classification of days in a year based on local static variables.

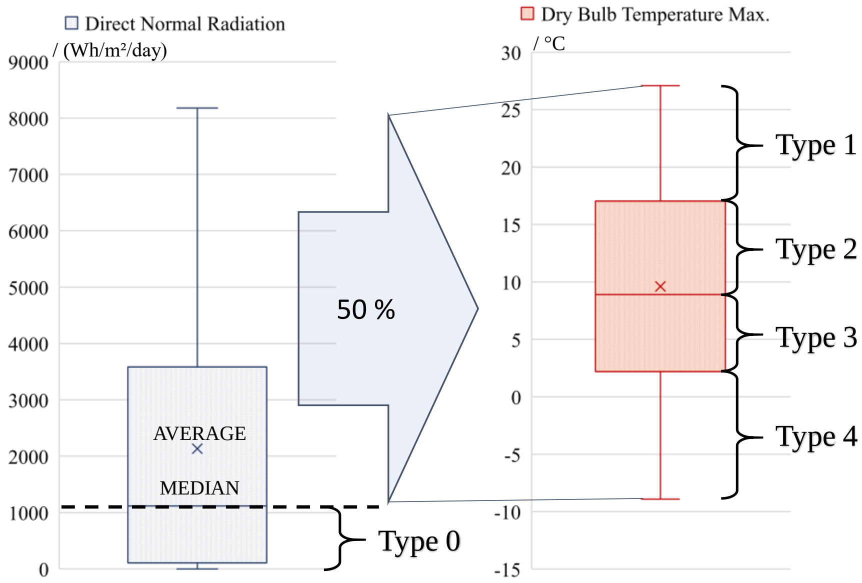


Figure 5. Example of climate days categorisation from annual weather data (values for Stockholm).

Table 5. Climate day types.

Type 0	DSR below median (50 % of the year, cloudy, low radiation)
Type 1	DSR above median, DBT.max in the fourth quartile (very warm)
Type 2	DSR above median, DBT.max in the third quartile (warm)
Type 3	DSR above median, DBT.max in the second quartile (cold)
Type 4	DSR above median, DBT.max in the first quartile (very cold)

All annual solar altitudes from the weather file were separated into 3 sets of solar angle ranges: i) 0° to 15° - low angles, ii) 16° to 30° - medium angles, iii) 31° and above – high angles. From those sets, only the relevant solar vectors for south orientation were selected by isolating only the solar vectors that belong to a solar azimuth range of (-60)° and (+60)° from the south azimuth. The reason is that the reflectance of a glass surface is increased largely for angles of incidence higher than 60° (ASHRAE, 2017, p. 15.15).

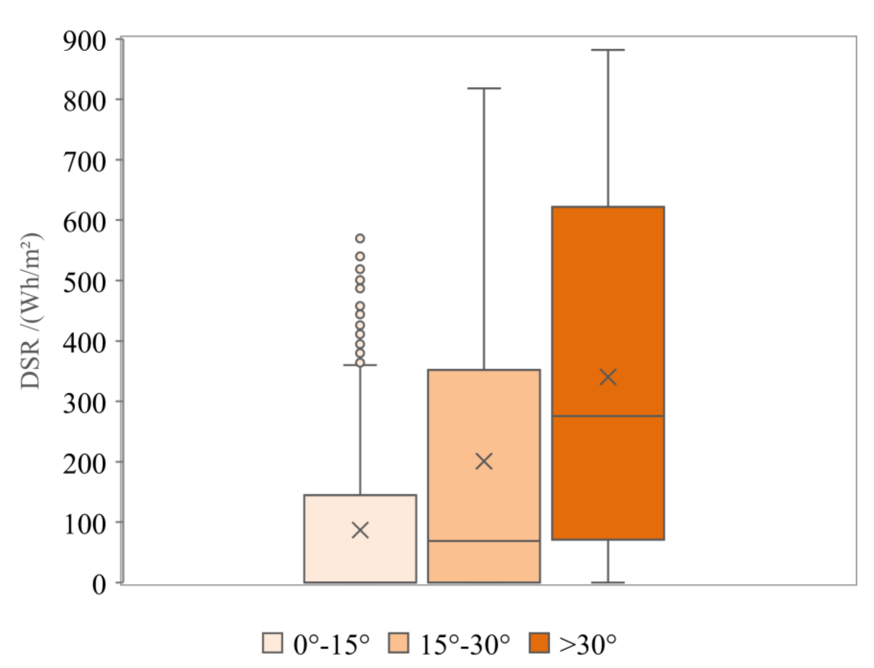


Figure 6. Example of hourly direct solar radiation (DSR) annual data separation into sets based on their corresponding solar altitude (Stockholm).

Thereafter, reference days were selected, ensuring that the solar position at noon in a reference day also belongs to the respective solar angle range. Expectedly, low solar angles are concurrent with climate days of type 0, 3, and 4, furthermore, low angles yield lower solar radiation as seen in Figure 6. The combinations of solar altitude angle and climate day type for selection of reference days were chosen as follows:

A. Low angle, Climate day type 4
B. Medium angle, Climate day type 3
C. High angle, Climate day type 2
D. High angle, Climate day type 1

Reference days prediction method was examined for Stockholm climate data, WWR 84 % with clear glass. For this purpose, three cases were contrasted: i) base case model with no external shading, ii) smaller overhang 100 cm, iii) larger horizontal louvers 40 cm. Performance was evaluated through measures of energy use, operative temperature, hours with electric lights turned on, and hours with DGP above 0.4. Another 'side study' investigating 'cooling conditions' was carried out to find the sensitivity of outdoor temperature and solar heat gain on occurrence of cooling hours.

3.3.2 Shading benefit index

In order to assess the benefit of a certain shading solution in an early design stage for a given climate, without building parameters inputs and without simulations (as mentioned in section 2.2), it is proposed to solely use weather data. Two types of shadings with their main function were recognised:

a) External shading, as reduction of solar heat gain (section 3.3.2.1),
b) Internal shading, as glare control (section 3.3.2.2).

In the next sections, new methods of shading benefit evaluation were proposed. They are meant to serve as an early design stage tool for a quick recognition of climate related issues that could potentially be solved with a type of a shading device or with outdoor air. These new ways are not aiming to 'reinvent the wheel' and cannot substitute annual simulations but can help recognise the need for shading devices in a given climate to inform architects and designers before major decisions are made early in the design process. It should be noted that this is a completely new approach and as such should be treated with caution. The methods were further contrasted with annual simulation results in order to validate their relevance and usability.

In the next sections, a method of normalising and comparing results was used. This method will be further referred to as 'validation method'. The principle of its mathematical operations is seen in Figure 7. As a first step, values in each set A and B are normalised by means of division by a respective set's maximum value. This generates sets with values between 0 and 1. Further on, a difference for each cell, i.e. hour, between sets A and B is found, and the absolute value of that difference is then taken. As the last step, the resulting set of values is summed to produce a singular value. The lower the sum, the closer the correlation between analysed sets.

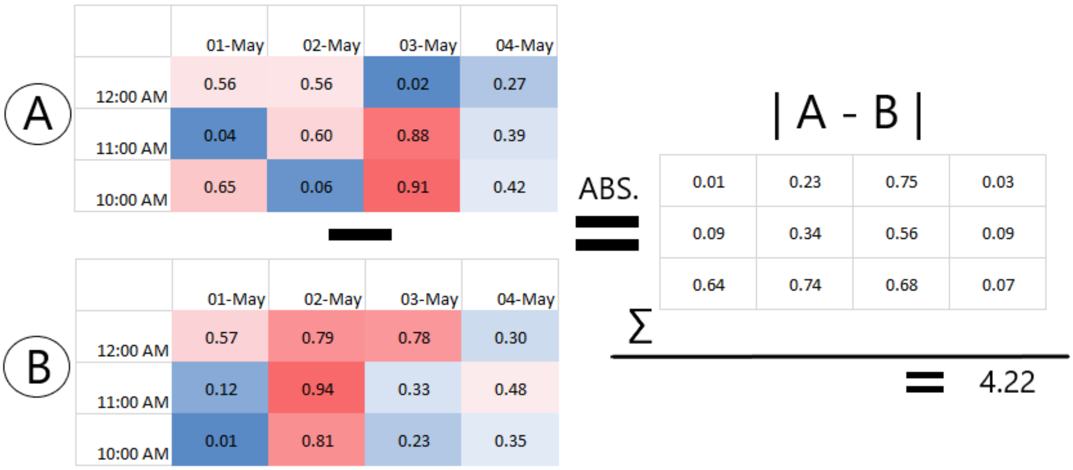


Figure 7. Example of validation method procedure shown for a fragment of a theoretical and randomised annual chart.

Additionally, such subtraction of sets, as shown in Figure 7, was carried out to compare any two study cases. This allowed to find the difference for each hour, which was often a reduction of e.g. cooling loads. In this case, it was not necessary to find the absolute values and the resulting values in a set were not summed, as they were plotted in an annual chart for further visual comparison (e.g. Fig. 62 & 64).

3.3.2.1 External shading

An external shading's primary function is deflection of solar rays to minimise solar heat gain (section 2.2) and its efficiency is climate-dependant. Higher solar angles are of higher intensity (Fig. 6 in section 3.3.1) and can be easily shaded with a horizontal shading geometry that does not obstruct daylight and view, therefore, external shading is expected to be more beneficial the higher the sun is above the horizon (Fig. 8). Similarly, orientation of the sun closest to south azimuth would be most energy intensive but also more feasibly shaded. Outdoor temperature may not affect the performance of the shading directly but lower outdoor temperatures enable 'free' zone cooling (section 2.4) that can be achieved by increasing the outdoor airflow through a mechanical system (active) or with openings through natural ventilation (passive). Thus, climate parameters, which are decisive in external shading benefit evaluation were identified:

- Solar altitude (position above the horizon) /°
- Solar azimuth /°
- Direct normal solar radiation /(Wh/m²)
- Dry bulb temperature /°C

Equation (1) that calculates external shading benefit index (ESBI) for every hour of the year was proposed:

$$ESBI = -\cos(Az + x) \cdot \sin(Alt) \cdot DSR \div 100 \quad [-] \qquad (1)$$

Where *Az* is a solar azimuth (180° as South), *x* is the fenestration orientation (0° is South, 90° is East and (-90)° is West), *Alt* is a solar altitude, and *DSR* is direct normal solar radiation. ESBI only expresses positive and unitless values, thus negative results should be culled as they refer to solar rays that do not fall on the window geometry, as seen from Figure 8.

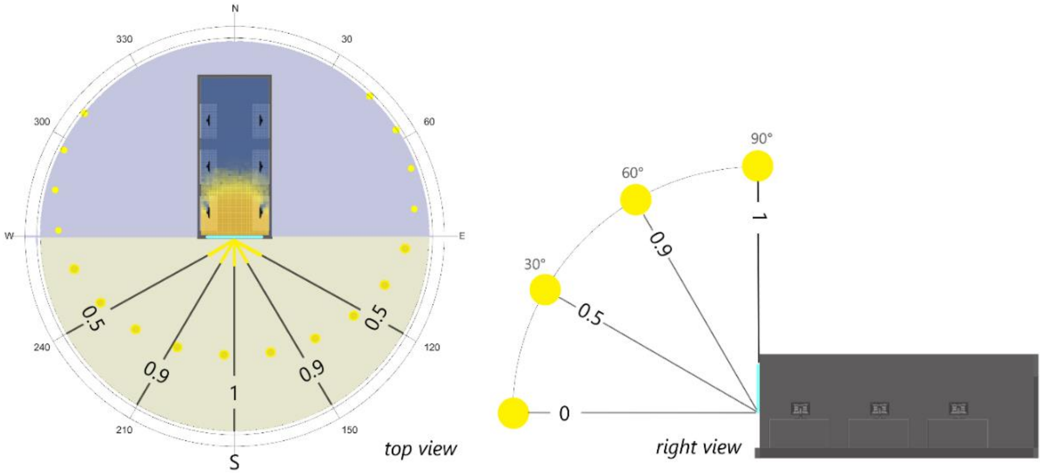


Figure 8. Possible values of '-cos(Az+x)' (top view) and 'sin(Alt)' (right view) from ESBI equation. Negative '-cos(Az)' for sun positioned at northern half (dark part) of sky dome.

Theoretically, the scale of ESBI ranges from 0 to 10.5 for the sun at zenith as the DSR yields at 1 050 W/m² ("Introduction to Solar Radiation," n.d.), however, in northern climates values above 7 are rather uncommon due to low solar angles. Values above 1 should be viewed as areas of considerable shading benefit for a well-insulated office with no outdoor air cooling. However, when a type of free cooling with outdoor air is designed for a building, the evaluation of ESBI is proposed to be calculated using the following equation:

$$ESBI.vent = -\cos(Az + x) \cdot \sin(Alt) \cdot DSR \cdot DBT \div 1500 \quad [-] \qquad (2)$$

Where *DBT* is outdoor dry bulb temperature. Again, negative results of ESBI.vent are invalid because, just like in the initial ESBI equation, they represent solar vectors that cannot hit the given surface geometry (Fig. 8). ESBI.vent is also unitless, but the values are not of the same scale as ESBI. Compared with ESBI in Eq.(1), ESBI.vent was further divided by a factor of 15, as it was assumed that outdoor temperatures above 15 °C might not cool as effectively (justification can be found later in 'Cooling conditions' side study in section 4.1.5, Fig. 13 & 14).

The upper ESBI.vent scale limit can go above 25 but for Sweden values higher than 12 are unlikely due to low temperatures. For values higher than 2, the benefit of external shading device can be observed. Values in range of 0 to 2 indicate that during this time free cooling might be possible. It is worth noting that the values in the scale range are relative and should not be taken at a face value, as they will vary for different locations due to climate specific relation between solar angles, radiation intensity, and temperatures. Thus, the recommended way of interpretation is to plot annual charts for Equations (1) and (2) with upper scale limited by the set's maximum value, and to contrast ESBI.vent with the original ESBI, in order to find which chart parts record a lowered index in a local scale, i.e. change of colour from upper ESBI scale to bottom ESBI.vent scale range. This will give an information when in a year span a free cooling strategy can be utilised to rid the zone of excessive heat. Consequently, the ESBI.vent method can help recognise the most critical periods for which external shading device should be designed.

3.3.2.2 Internal shading

Similarly, Equations (3) and (4) that calculate internal shading benefit index (ISBI) were proposed. As mentioned previously in section 2.2, internal blinds are best used for provision of visual comfort as they are not as efficient in solar heat gain protection as an external shading. A good example of such shading device could be blinds or curtains. Since the risk of visual discomfort is higher with low solar angles, solar altitude was put in a cosine function so the values on the right side of Figure 8 are the opposite.

$$ISBI = -\cos(Az + x) \cdot \cos(Alt) \cdot \sqrt{DSR} \quad [-] \qquad (3)$$

ISBI is unitless and values of more than 30 are not common, and an expected upper limit for a Swedish climate is around 25. Values above 7 indicate hours when disturbing glare can occur, which will be further observed. This method can serve as a tool for a quick recognition of periods where glare and visual discomfort are likely to occur. Since the visual discomfort is dependent more on the position of the sun rather than the strength of the solar rays, the DSR was square-rooted. The difference between using DSR and $\sqrt{\mathrm{DSR}}$ was analysed, and will be presented further.

The ISBI results were compared with simulated visual comfort assessments, i.e. DGP. Since there were two occupant workstations considered, two sets of DGP results were obtained for east and west separately. Those were combined into one set, further referred to as ‘combined DGP, by taking the maximum value for each hour. In order to find which of the ISBI equation approaches better matches the simulated combined DGP results, the values within sets of both versions – using DSR and $\sqrt{\text{DSR}}$, were analysed with the validation method (explained in section 3.3.2). The larger the resulting sum, the more divergent the ISBI values are from the corresponding simulated DGP.

A modified version of Equation (3) was proposed, in which cosine of solar altitude is squared. This way higher solar angles lose their impact and the values become smaller than in original ISBI. Since it is predominantly low solar angles that are responsible for visual discomfort, and since the higher the angles the larger the DSR values, it was checked whether the new Equation (4) for ISBI.mod is more suited for early stage visual discomfort assessment.

$$ISBI.mod = -\cos(Az + x) \cdot \cos(Alt)^2 \cdot \sqrt{DSR} \quad [\text{-}] \tag{4}$$

The scale of ISBI.mod is the same as of ISBI, and the shifts of values ranges are negligible.

This way of early prediction approach to visual comfort assessment can potentially save designers a lot of time, as annual daylight simulations, especially glare, can be very time consuming. In fact, when running a Radiance or Daysim simulation through Honeybee 0.0.64, a Windows command window carries the following warning: “this simulation may take several minutes to hours”. The above proposed equation for shading benefit indices would only take seconds to complete, provided that a simple calculation tool was developed.

4. Results

4.1 Side studies

4.1.1 Shading reflectance sensitivity

The study investigated three settings of shading reflectances (as explained in section 3.1.6) and its impact on electric lighting use, which is shown in Figure 9. It can be observed that external shading reflectance has little impact on the lighting schedule and by extension, the operation of electric lights. With higher reflectance, the electric lights use drops only by circa 2 %, which for the investigated case resulted in 10 kWh yearly savings. In further annual simulations, 20 % reflectance of the shading surfaces was used.

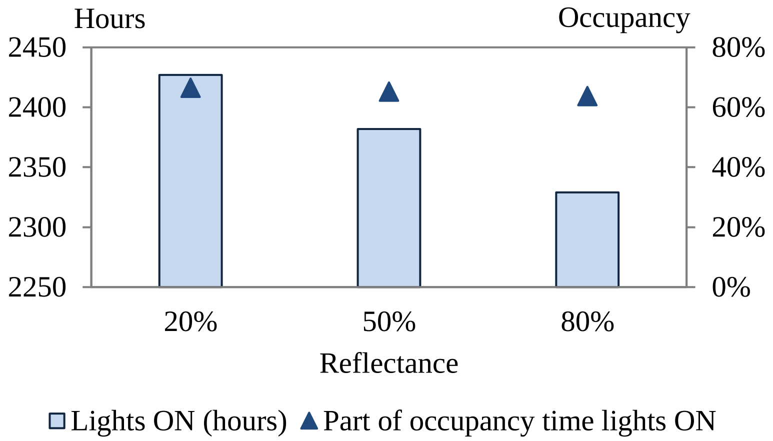


Figure 9. Annual electric light use for Stockholm with 5HL40 shading type and different shading reflectances.

4.1.2 Daylight simulation quality sensitivity

Daylight quality parameters of lower setting (previously seen in section 3.2.1, Table 4) were contested against higher quality settings, comparing electric lights use for corresponding large-sized overhang and brise-soleil shading types. Analysing results in Table 6, it is apparent that higher quality of simulation parameters yields considerably lower lighting use as the zone sensor records more daylight, however, the difference between OH and BS changes only from 0.9 % for lower quality simulation to 1.8 % for higher quality.

Table 6. Occupancy time electric lights are on.

	Lower quality	Higher quality
OH 200	72.4 %	66.6 %
BS 200	71.5 %	64.8 %

4.1.3 Thermal zone modelling

The difference in thermal results was investigated for Stockholm climate, testing a single thermal zone model against a two zone model. Figure 10 represents the percentage of occupancy time when the lights are turned on for each zone. It can be seen that having just one centrally placed sensor, the zone close to the window (1 of 2) will receive too much artificial lighting whereas the zone at the back (2 of 2) will be slightly underlit. Single zone is less responsive to local lighting conditions. The difference between electric lights use in the back zone (2 of 2) and in a single zone becomes less for a larger size window.

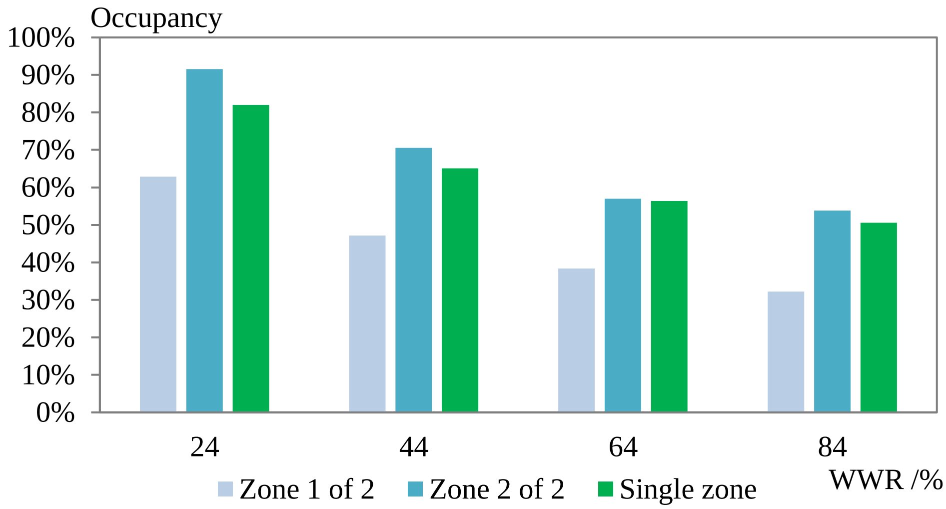


Figure 10. Part of occupancy time when electric lights are on for a single zone and a two-zone model.

Single zone modelling resulted in higher total electric lighting use, which subsequently contributed to an annual increase in cooling and decrease in heating load due to higher internal lighting heat gains (Fig. 11). However, total EUI for a single zone model increased only by 3 % to 6 % in annual terms, and further in the study, thermal modelling was simplified and reduced to a single zone, having just one central lighting sensor (Fig. 2).

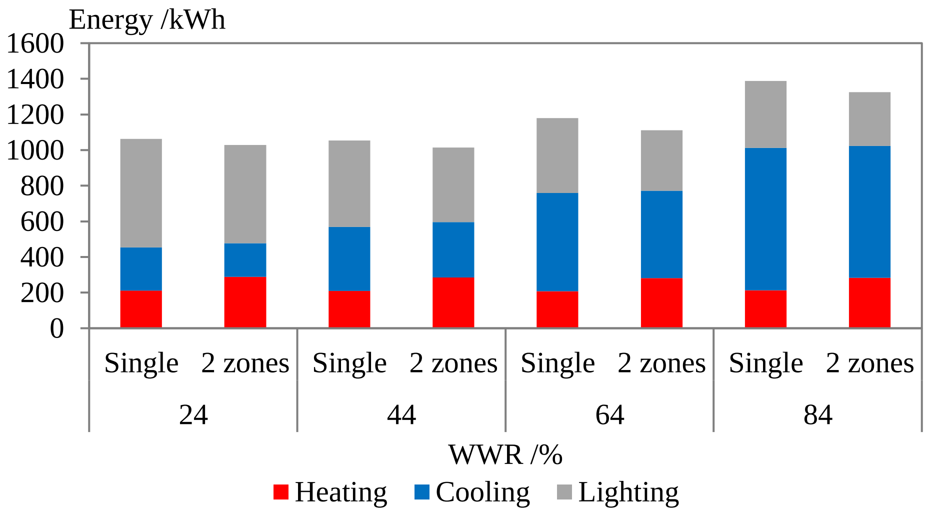


Figure 11. EUI comparison for a single and a two-zone model.

4.1.4 Reduced solar gain, increased lighting gain

The side study, previously introduced in section 3.2.2, investigated the relationship between visual light and thermal radiation that are both concurrently transmitted through a window into a zone when the sun is shining. Figure 12 shows hours in a year, which are above Miljöbyggnad solar heat gain thresholds for the base case without an external shading device. Addition of an external shading (OH100 & OH200) blocks a portion of solar rays hitting the window surface, thus reduces the number of hours which are above the thresholds in relation to the base case. These reduced solar heat gain hours, which now comply with Miljöbyggnad requirements, can be seen in the graph for OH100 and OH200. Comparing the reduction reached by an external shading with the base case hours above the threshold, it can be observed what portion of high solar heat gain hours a shading device was able to eliminate. For a smaller overhang (OH100) the reduction revolves roughly around 50 %, while a larger shading (OH200) culled around 90 % of hours. Labels above the columns represent the percentage of hours that require the use of electric lighting due to insufficient daylighting (lights on).

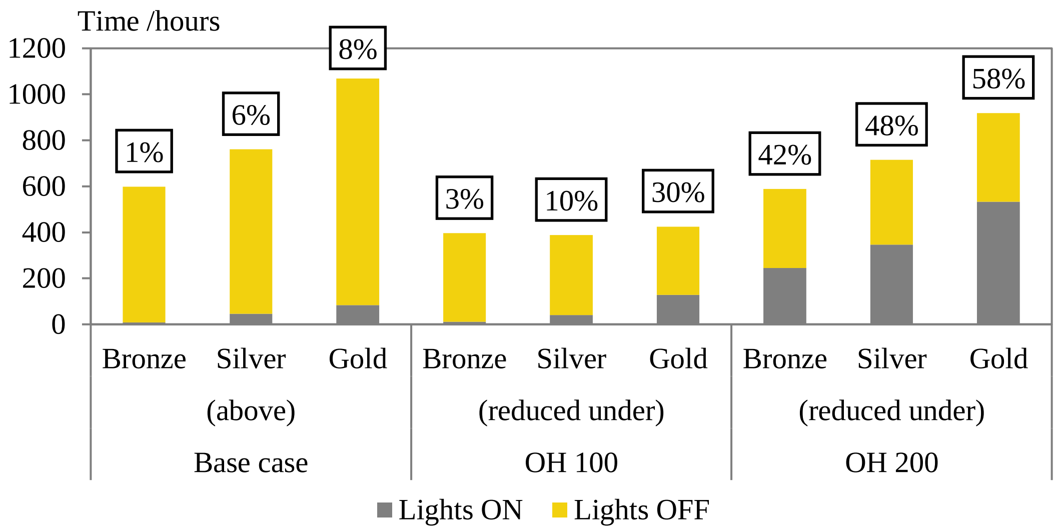


Figure 12. Solar heat gain hours above (base case) and reduced to below (shadings) Miljöbyggnad thresholds (Stockholm, clear glass WWR 84 %).

Only a small percentage of hours with solar heat gain for the base case does not receive sufficient daylight at the sensor point and thus requires lights switched on. Reduction of solar heat gain by shadings contributes to an increase in electric lighting use, more so when reaching for a higher standard or when having a larger size shading. A large share of hours comply with Miljöbyggnad criteria for OH200, but concurrently, about half of those hours fail to meet the lighting threshold, meaning that, even though solar heat gain is reduced, electric lighting will augment internal heat gain.

4.1.5 Cooling conditions

Cooling conditions were investigated by simultaneous analysis of two parameters: outdoor temperature and internal solar heat gain per square meter of floor area (as mentioned before in section 3.3.1). Figures 13 and 14 show hours when cooling occurs in a year for Stockholm climate – clear glass case without any shading device.

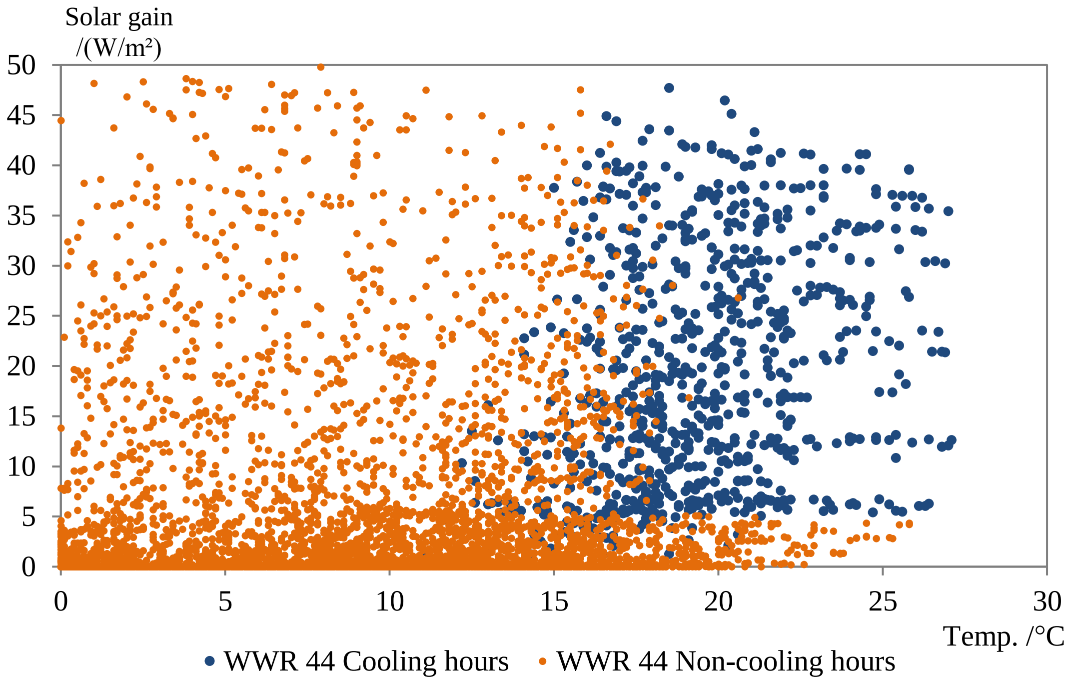


Figure 13. Visualisation of cooling hours distribution (Stockholm, clear glass WWR 44 %).

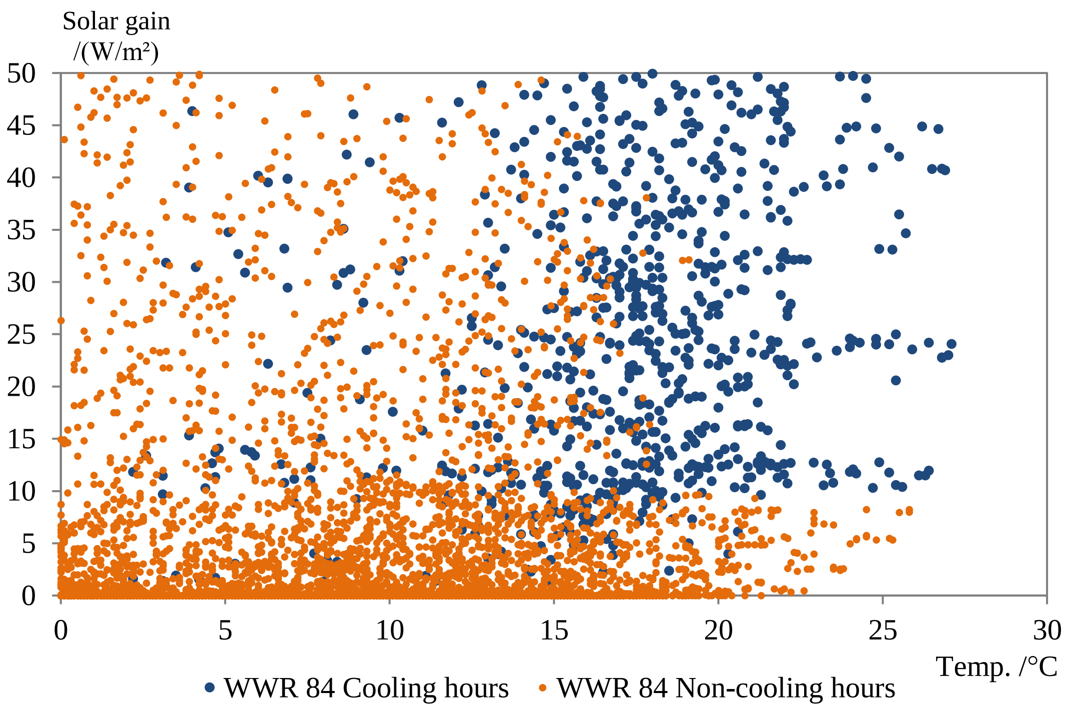


Figure 14. Visualisation of cooling hours distribution (Stockholm, clear glass WWR 84 %).

Comparing Figure 13 with Figure 14, it can be observed that, in the case of a larger window with WWR 84 %, cooling hours are spread widely across the chart, which means that increasingly more hours with rather low outdoor temperatures are experiencing overheating. Whereas, in case of a smaller size window with WWR 44 %, a more distinct line separating the two sets of cooling and non-cooling hours can be noticed and the borderline lays approximately at 15 °C - 17 °C outdoor temperature, which was the motivation behind selection of ‘15’ as an additional dividing value for ESBI.vent - Equation (2), as compared to ESBI - Equation (1). Division by that number was meant for adjusting the resulting scale of ESBI.vent in accordance to limitations for outdoor air temperature in event of natural ventilation, which was found to be close to 15 °C.

The existence of cooling ours with low solar heat gain and/or low outdoor temperature suggests that cooling loads may be sometimes predetermined by hours leading up to the current conditions, as accumulation of heat would impact the loads.

4.2 Annual performance

The results are presented for two climates and two window sizes, and for each of the four cases in the following subsections nine graphs in each were plotted.

4.2.1 Stockholm WWR 44 %

Figure 15 shows results of electric lights operation for investigated external shading cases, distinguishing between clear and selective glass glazing type, as well as comparing the impact of internal blinds operation. While there are distinct differences in electric lighting use between the external shading cases when no internal blinds are considered, they diminish when internal blinds are deployed. The results are also visibly trimmed and levelled for selective glass cases, as the internal lighting conditions are less sensitive to changing outdoor illuminances in the presented Stockholm climate scenario.

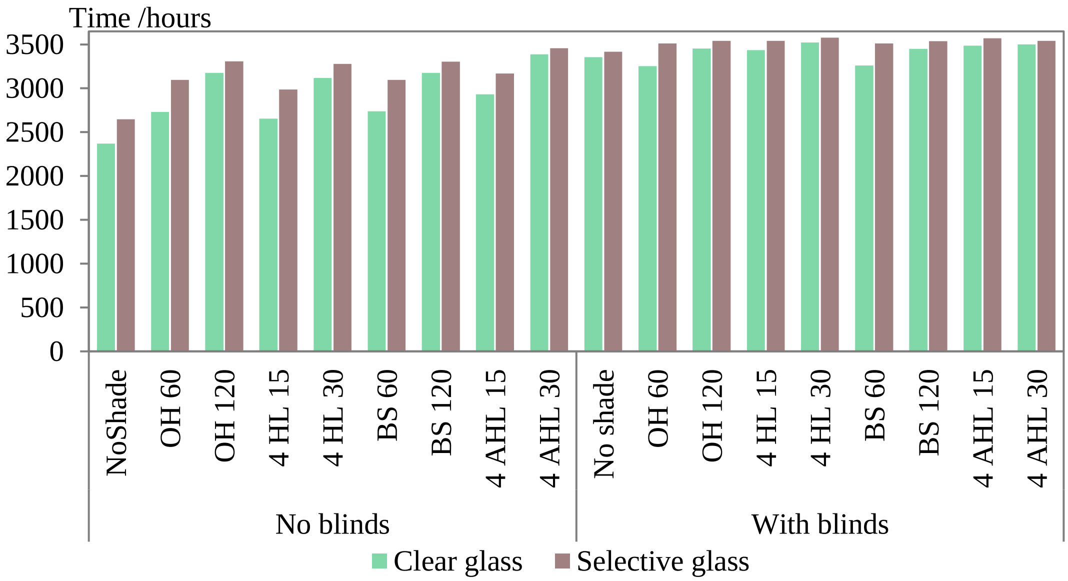


Figure 15. Hours of electric lights operation (Stockholm, WWR 44 %).

The same information about the use of electric lights can be found in Figures 16 and 17, this time expressed as a percentage of occupancy time that the lights are switched on. The charts show results of daylight and visual comfort for study cases that incorporate glare driven operation of internal blinds. Visual comfort is described by view to the outside (section 3.2.1), thus this parameter should be maximised, while use of electric lights should be minimised. Comparing the charts (Fig. 16 & 17) for clear and selective glass, it can be noted that the difference between corresponding fenestration cases in view to the outside is rather small, which suggests that selective glass does not resolve the issue of glare very well. The reduction of disturbing glare was no more than 4 % of occupancy time.

An observation can be made regarding multiple horizontal louvers as an external shading geometry. With less view to the outside than overhang type geometries (Fig. 16 & 17), it was shown that horizontal louvers yield more glare, and at the same time extend the use of electric lights. Previously in Figure 15, it was seen that horizontal louvers without internal blinds record less hours of electric lighting than a corresponding overhang or a brise-soleil, which evidently is the opposite when glare is considered ('with blinds' cases). Altogether, horizontal louvers can cause higher energy use than an overhang as seen in Figure 19.

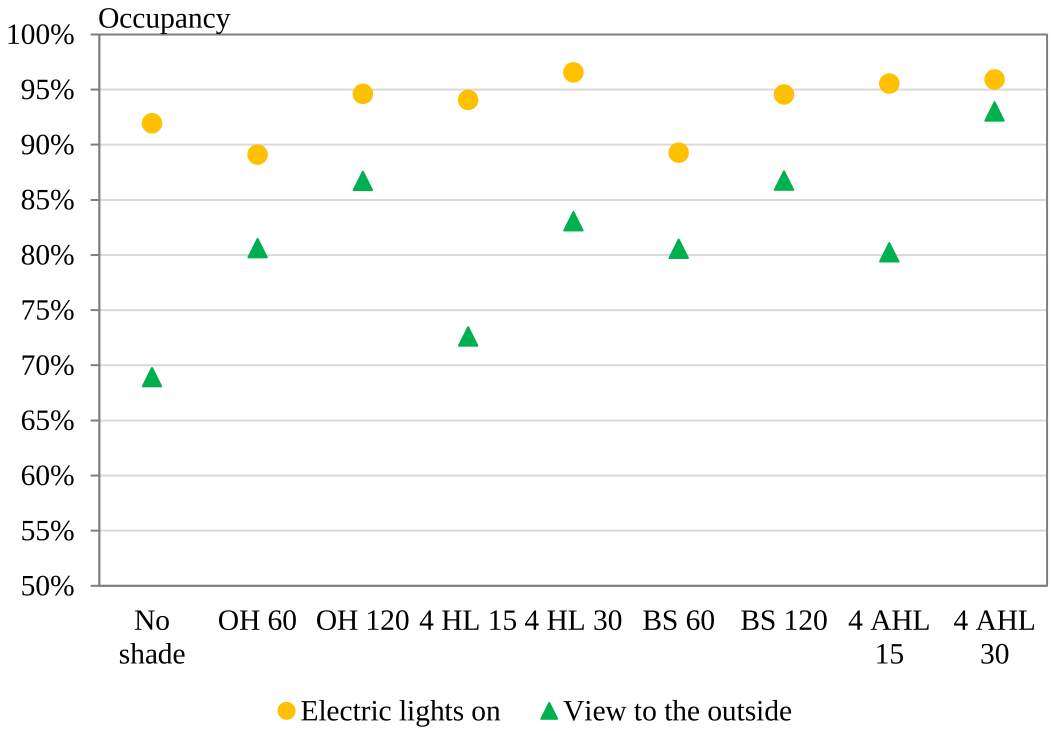


Figure 16. Percentage of annual occupancy time with lights-on and view-out (Stockholm, clear glass WWR 44 %).

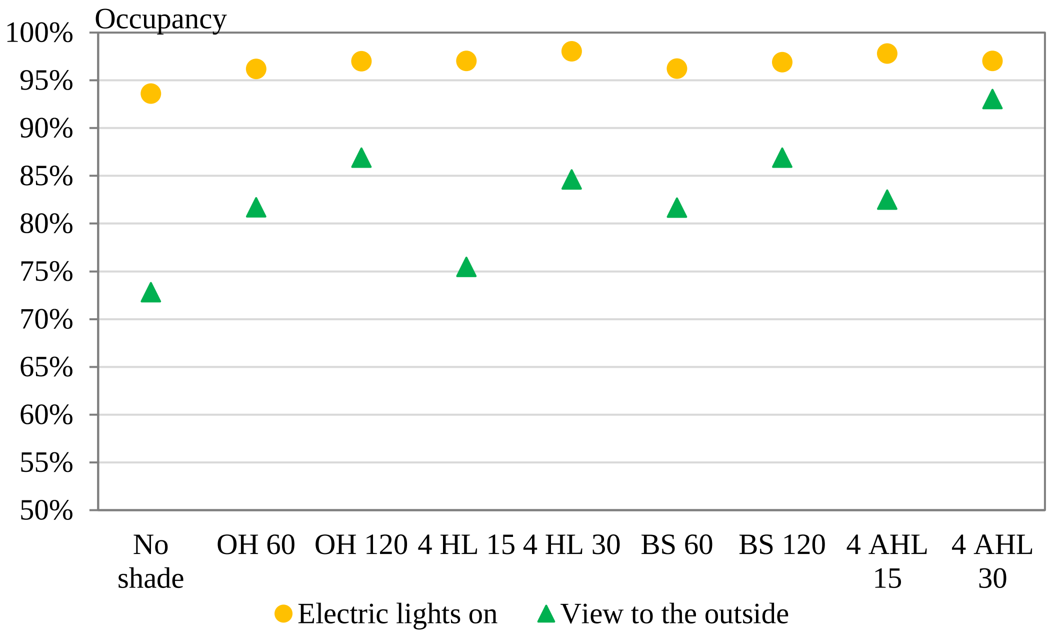


Figure 17. Percentage of annual occupancy time with lights-on and view-out (Stockholm, selective glass WWR 44 %).

Selective glass window for the base case with no external shadings results in lower EUI (Fig. 18). Including the operation of internal blinds into the annual energy simulations significantly increases the total energy use, therefore, results in Figure 19 show fenestration cases with the internal blinds. Overall, there are only slight differences between corresponding clear and selective glass annual energy use and account for less than 5 % in favour of selective glass as far as external shadings are considered.

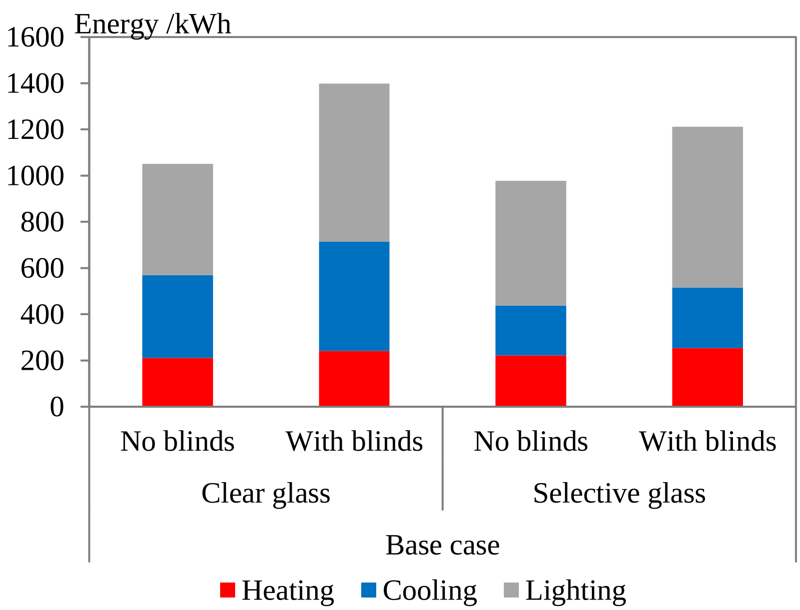


Figure 18. Energy use for base case (Stockholm, WWR 44%).

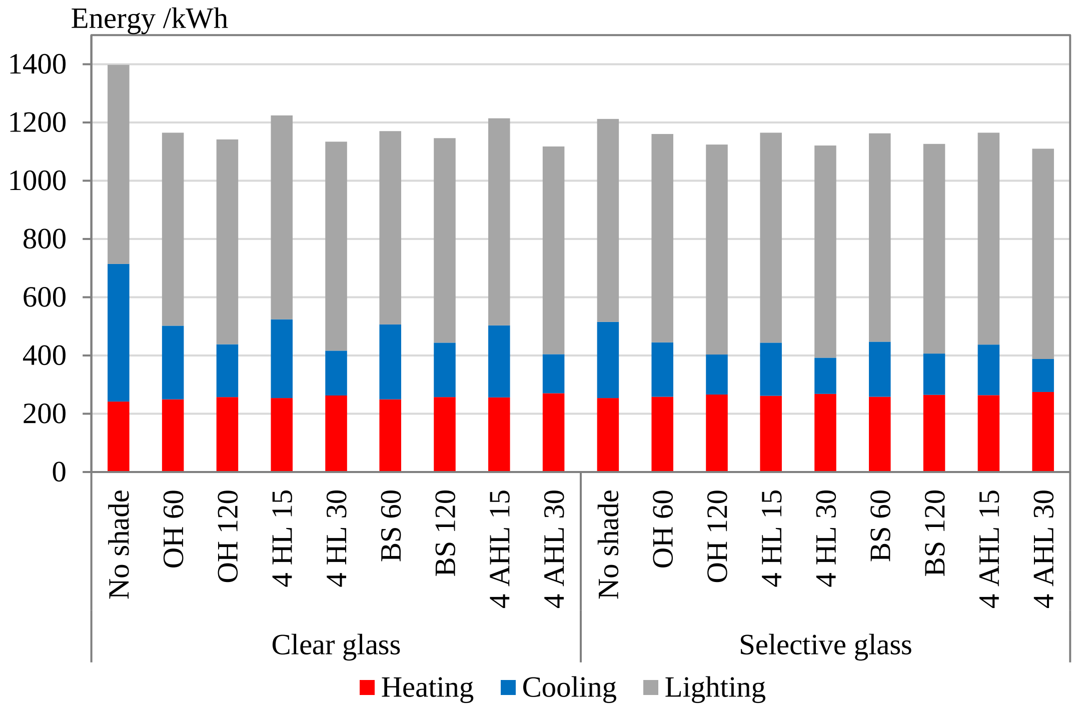


Figure 19. Energy use for studied cases with internal blinds (Stockholm, WWR 44 %).

Figures 20 and 21 show results related to thermal comfort (section 3.2.2). As seen from Figure 20, which presents hours with high solar heat gain, selective glass ensures compliance with Miljöbyggnad Gold solar heat gain standard, as for any shading case solar heat gain does not exceed 22 W/m² in the whole climate year. Only few external shading cases with clear glass achieve similar results.

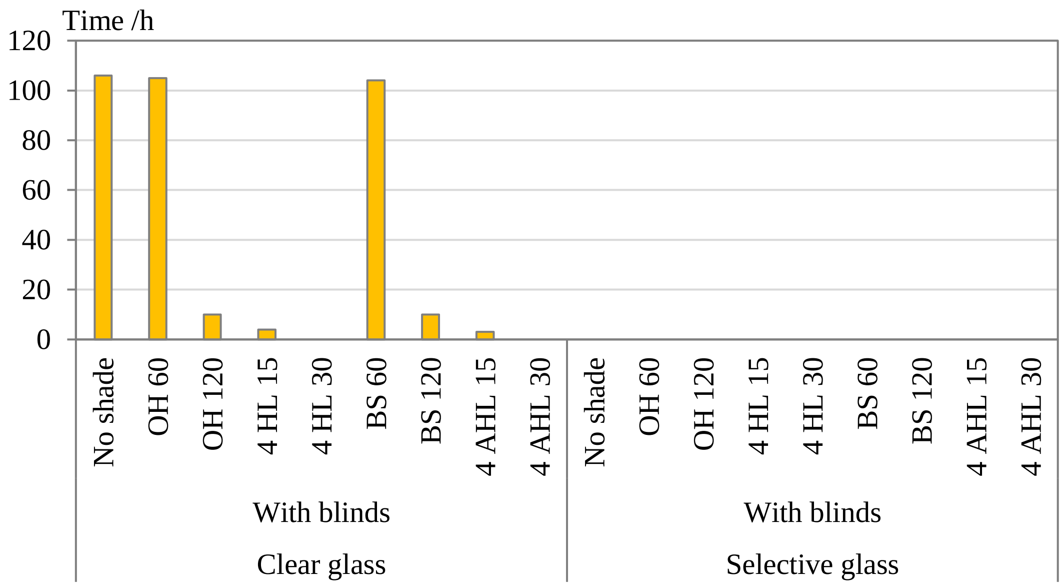


Figure 20. Number of hours in a year that exceed Miljöbyggnad Gold solar heat gain threshold of 22 W/m² (Stockholm, WWR 44%).

Selective glass is also better at reducing operative temperatures (Fig. 21), nonetheless, clear glass with external shadings does not exceed 10 % occupancy time when operative temperatures are above the air cooling setpoint of 25 °C. It was also found that in any case, operative temperature during occupancy does not fall below 18 °C. Cooling peak loads are expectedly lower for selective glass, though, the differences are less prominent for large shading sizes (Fig. 22). Both of the graphs show significant improvements in thermal comfort and system sizing when external shading is applied.

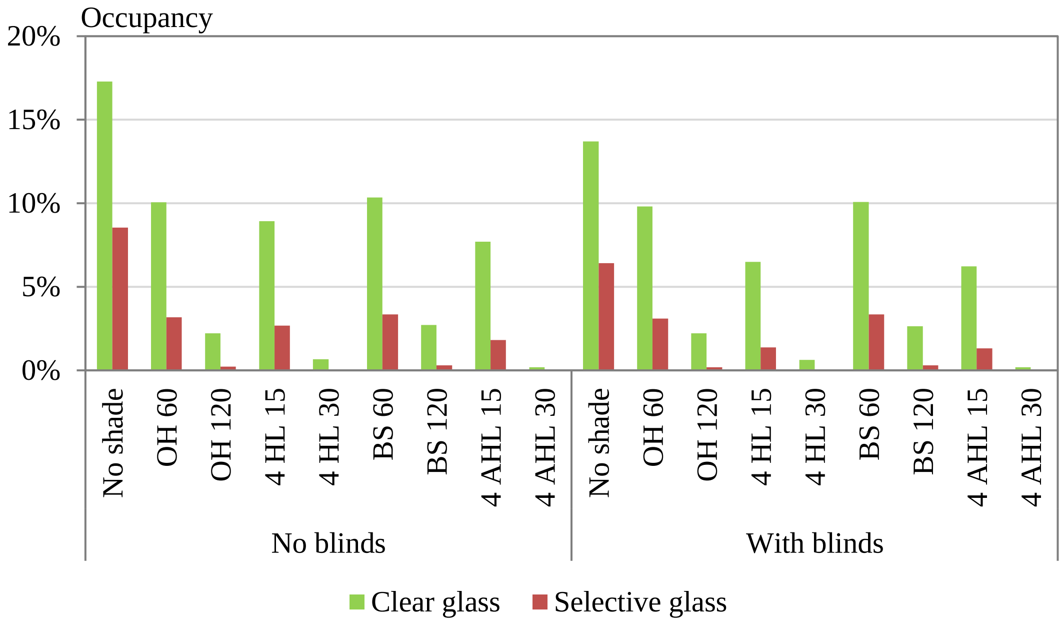


Figure 21. Part of occupancy time when operative temperatures exceed 25 °C (Stockholm, WWR 44 %).

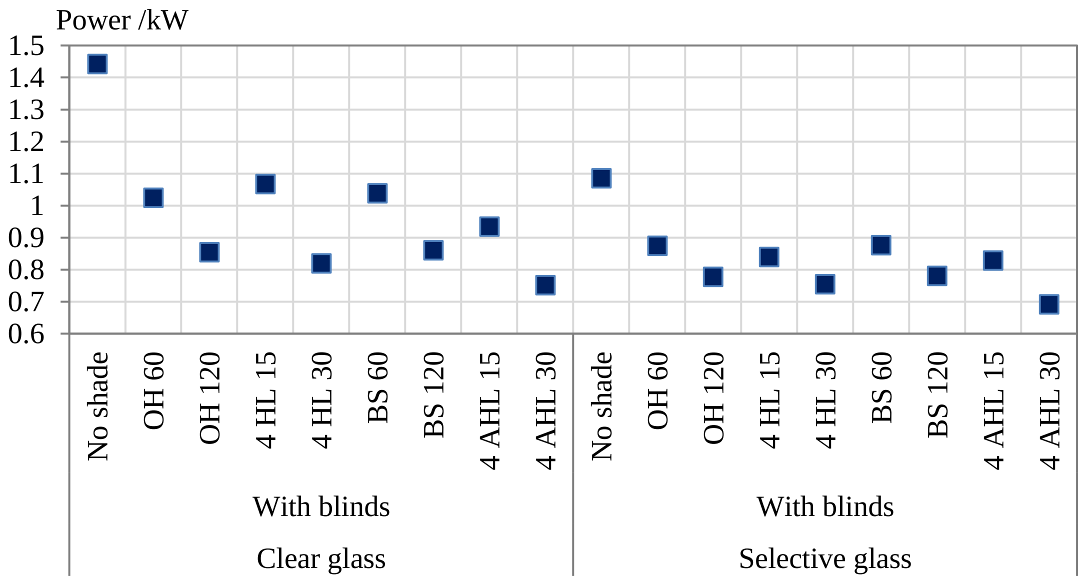


Figure 22. Cooling peak loads (Stockholm, WWR 44 %).

Moreover, if an outdoor air cooling strategy is applied in Stockholm climate conditions, it showed to be very effective in reducing cooling energy loads even further (Fig. 23). The strategy involved an air-side economiser added to a mechanical system, described in section 3.1.3.

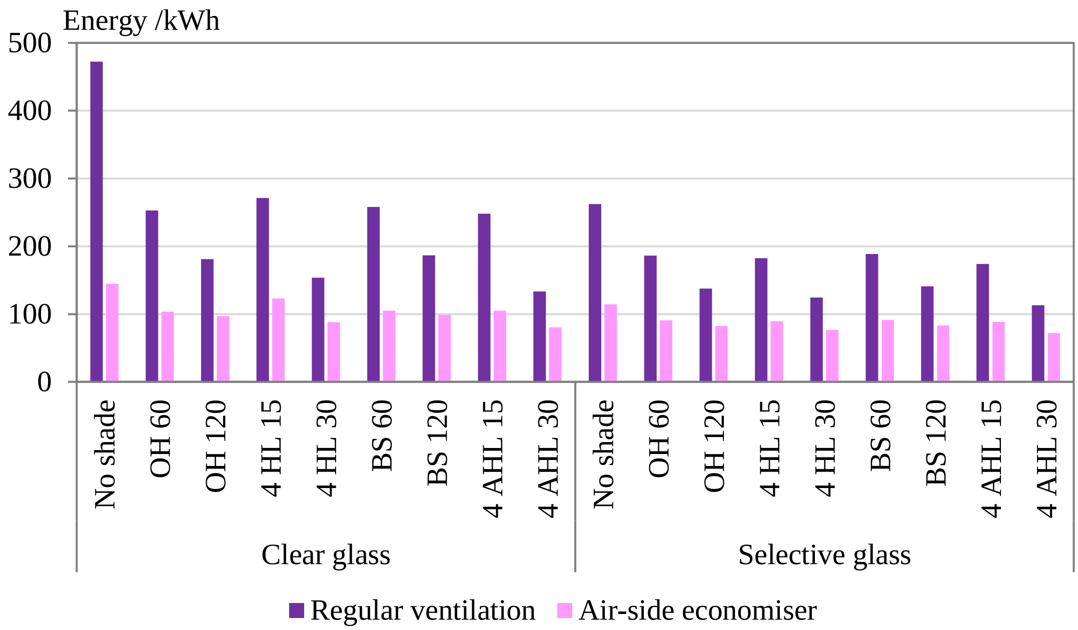


Figure 23. Annual cooling energy use (Stockholm, WWR 44 %).

4.2.2 Copenhagen WWR 44 %

Figure 24 shows electric lighting use duration over a year in Copenhagen. Similar patterns to those of Stockholm WWR 44 % occur, except for horizontal louvers. In Figures 25 and 26 it can be seen that horizontal louvers do not cause more glare hours than an overhang or a brise-soleil, therefore, the electric light use may be actually smaller in comparison (e.g. Figure 24, clear glass 'with blinds': OH60 and 4HL15). The observed difference between Stockholm and Copenhagen results concerning horizontal louvers geometry can be attributed to local insolation intensity and frequency variations. Angled horizontal louvers shadings succesfully reduce glare and ensure that the occupants have a view to the outside for almost an entire year (e.g. Fig. 25), however, this comes at a cost of daylighting, as the light provided by the sun is barely ever enough to maintain the required lighting level.

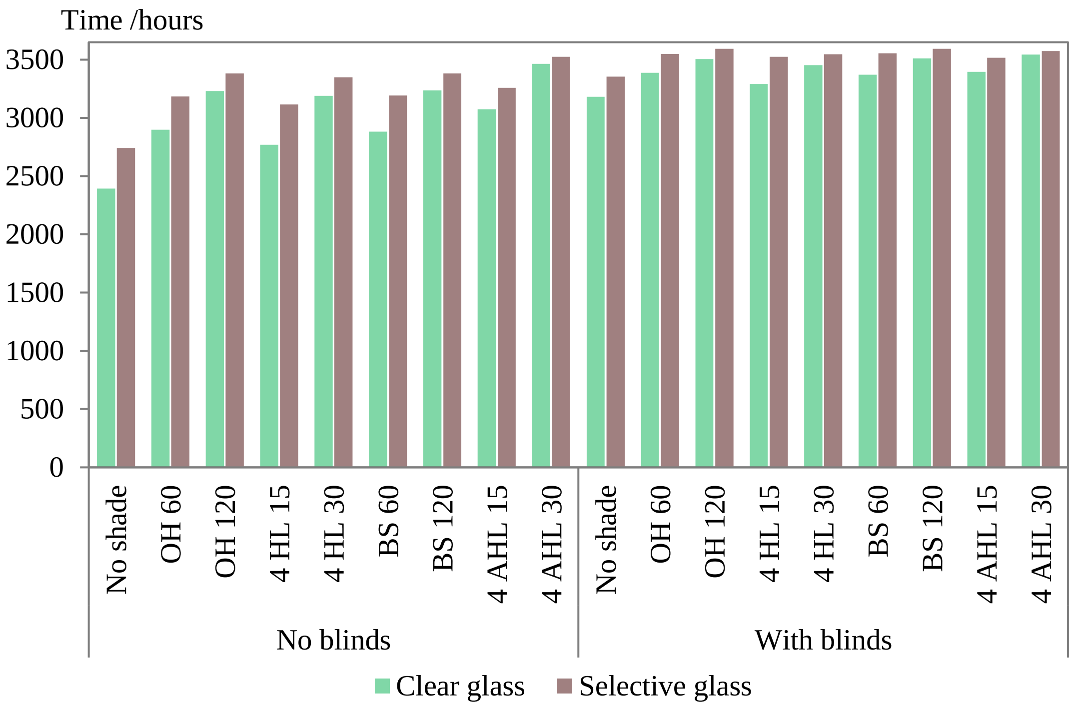


Figure 24. Hours of electric lights operation (Copenhagen, WWR 44 %).

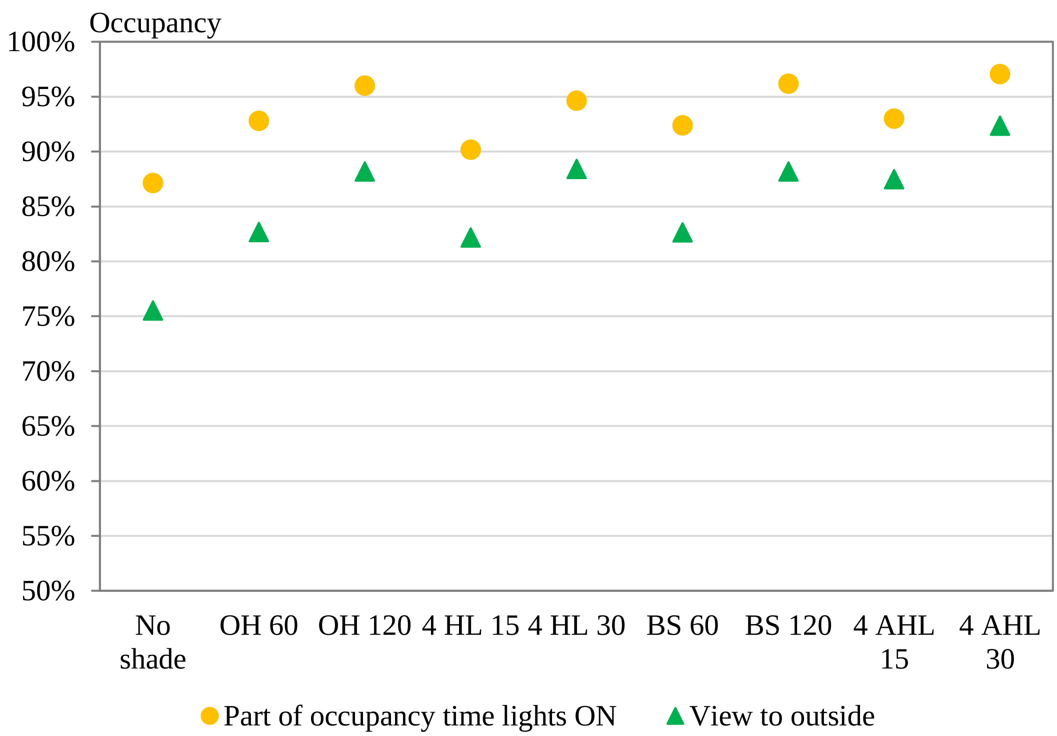


Figure 25. Percentage of annual occupancy time with lights-on and view-out (Copenhagen, clear glass WWR 44 %).

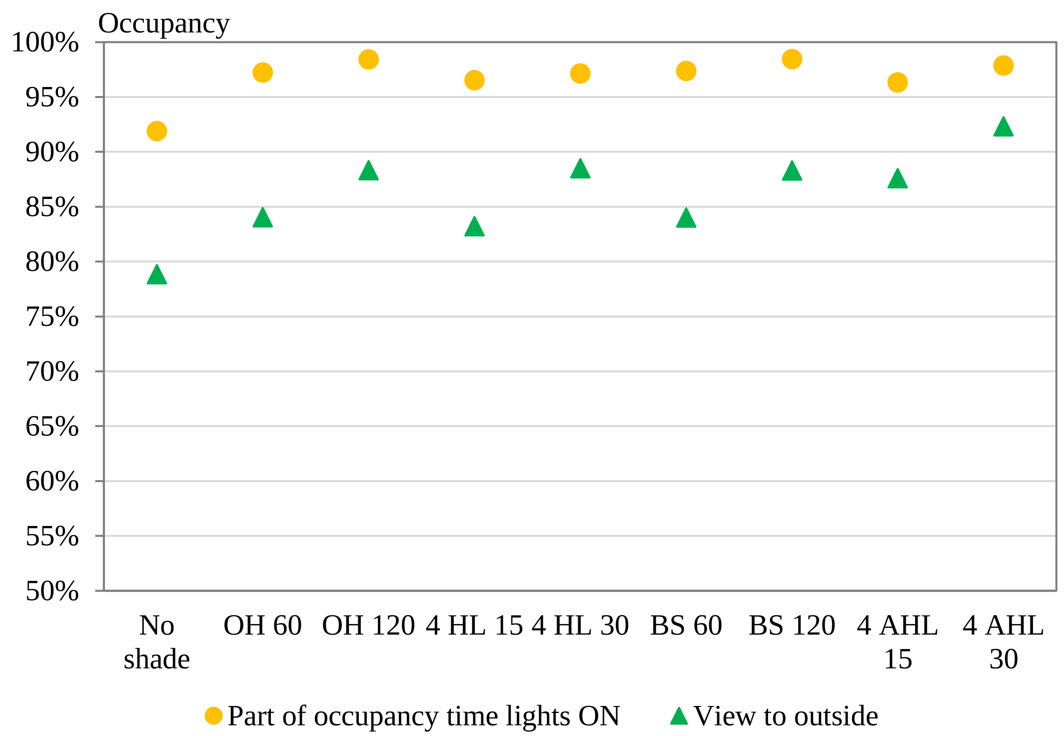


Figure 26. Percentage of annual occupancy time with lights-on and view-out (Copenhagen, selective glass WWR 44 %).

Energy results for the small case window in Copenhagen are presented in Figures 27 and 28. Use of blinds increase the EUI (Fig. 27). It is worth noting that heating use is practically unaffected by changes in fenestration design (Fig. 28). Whether selective or clear glass WWR 44 %, a larger external shading size of a certain type always recorded lower annual energy use. In case of Copenhagen annual weather, horizontal louvers type of shading allows higher energy savings than a corresponding overhang geometry (e.g. OH120 and 4HL30 for clear glass in Fig. 28).

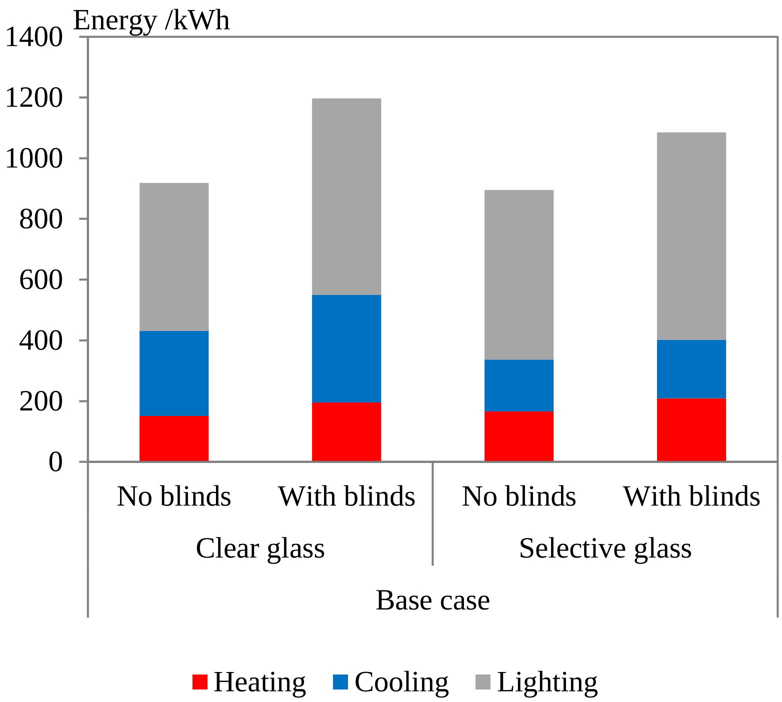


Figure 27. Energy use for base case (Copenhagen, WWR 44%).

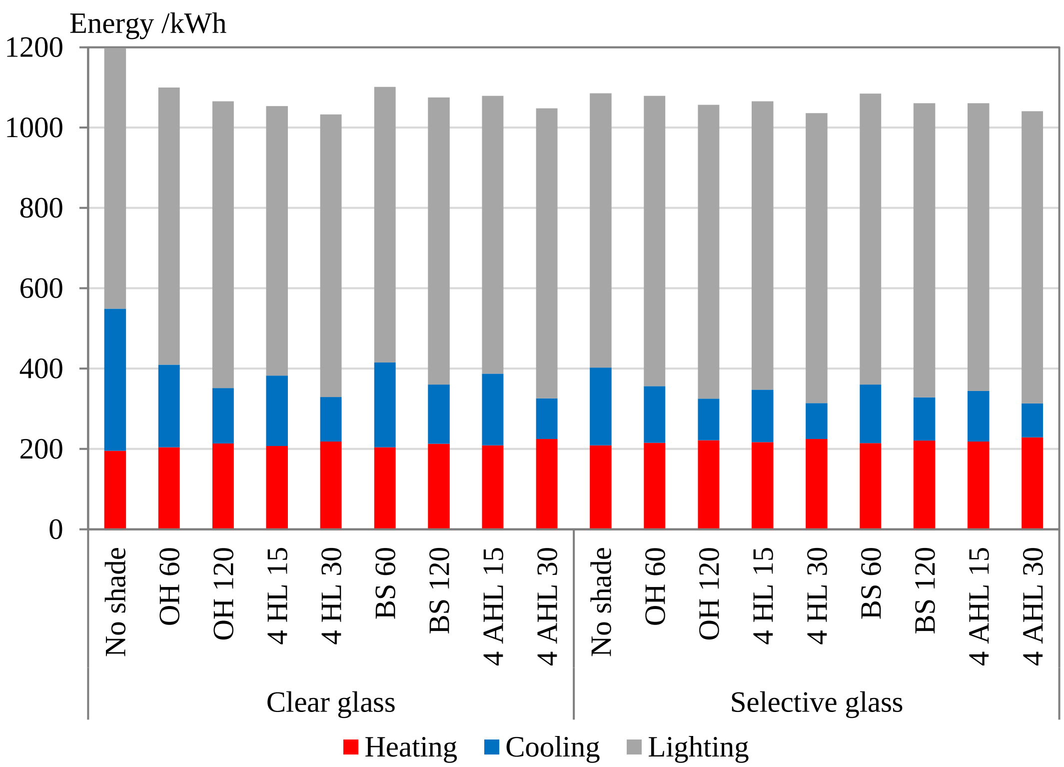


Figure 28. Energy use for studied cases with internal blinds (Copenhagen, WWR 44 %).

It can be seen from Figure 28 that there are more hours above Miljöbyggnad Gold threshold in Copenhagen than with the same small window size in Stockholm (seen in section 4.2.1), even though it is known that Stockholm is more sunny, but less frequent use of internal blinds in Copenhagen means that more solar gains are allowed to enter through less obstructed glazing.

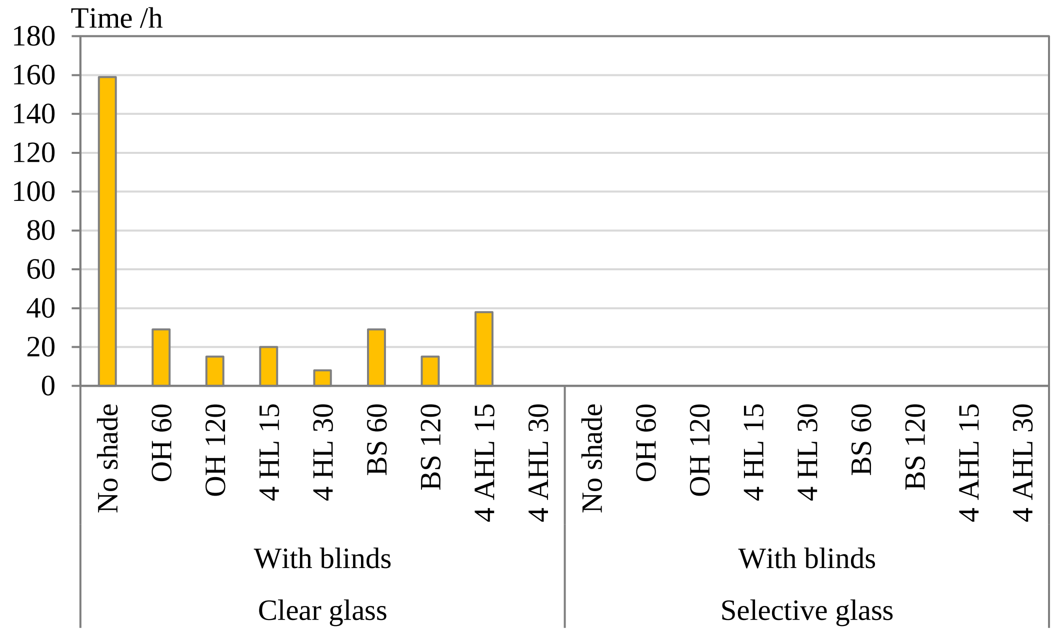


Figure 29. Number of hours in a year that exceed Miljöbyggnad Gold solar heat gain threshold of 22 W/m² (Copenhagen, WWR 44%).

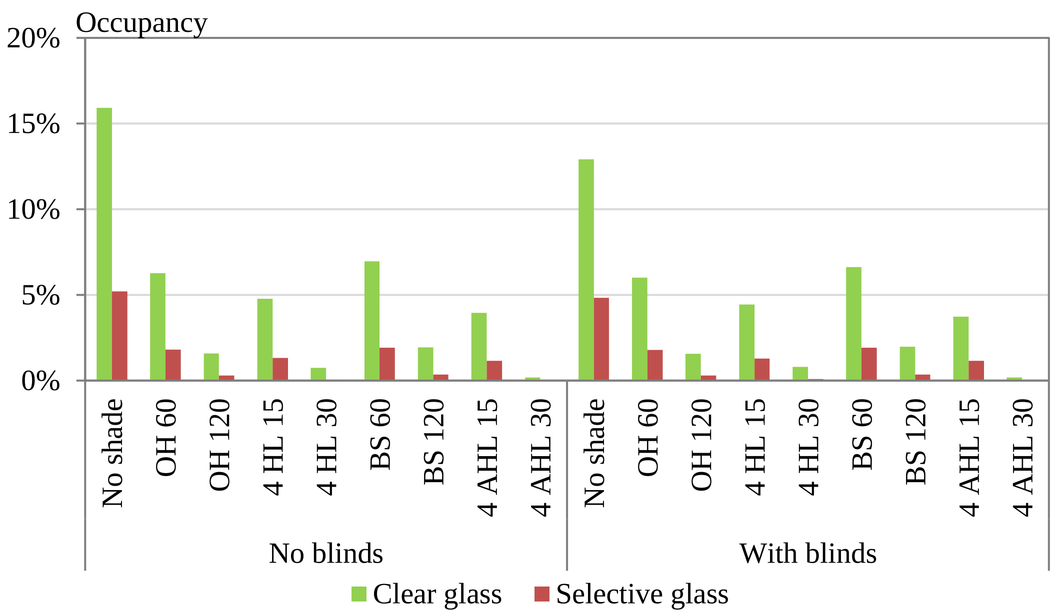


Figure 30. Part of occupancy time when operative temperatures exceed 25 °C (Copenhagen, WWR 44 %).

For all cases with external shadings, the occurrence of operative temperatures exceeding above 25 °C was kept well below 10 % of occupancy time (Fig. 30), and the operative temperature also never fell below 18 °C. Similarly to Stockholm, operative temperatures and cooling peak loads are smaller for selective glass, and the difference is most noticeable for smaller size shadings (Fig. 30 & 31). Also, the addition of an air-side economiser to the ventilation system substantially reduced cooling loads for Copenhagen climate as well, as seen in Figure 32.

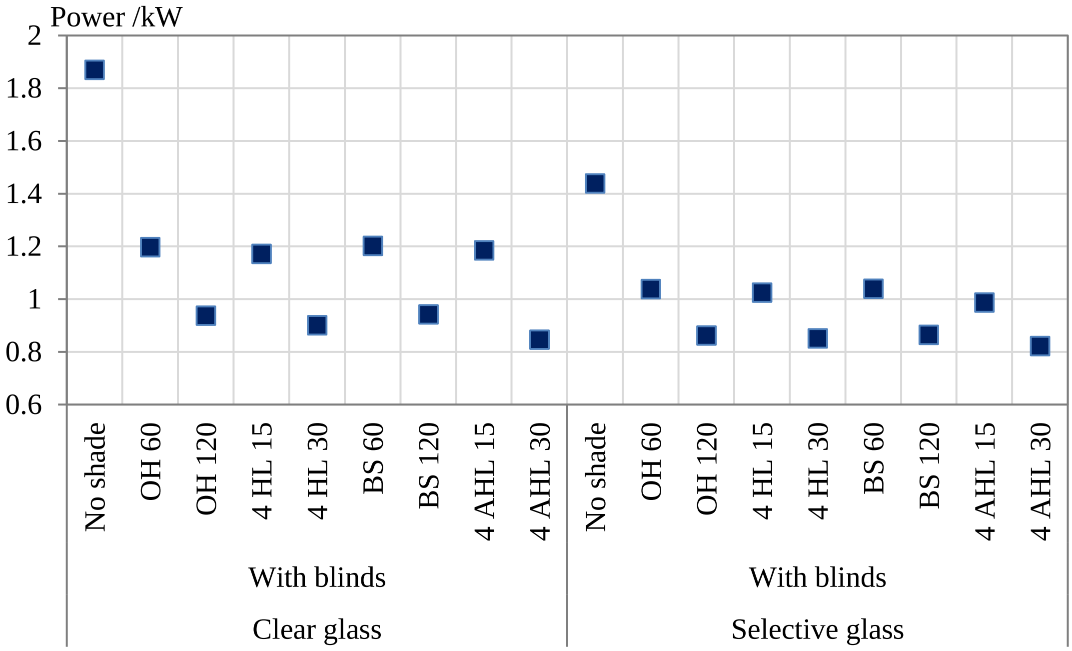


Figure 31. Cooling peak loads (Copenhagen, WWR 44 %).

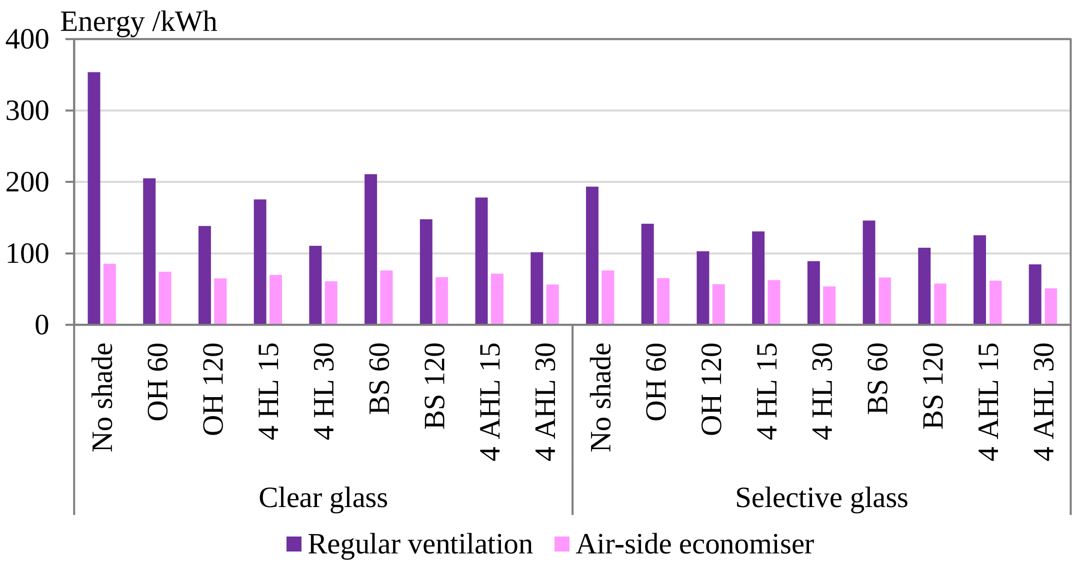


Figure 32. Annual cooling energy use (Copenhagen, WWR 44 %).

4.2.3 Stockholm WWR 84 %

Large window in Stockholm climate shows even higher disproportion between the simulated electric lighting use results with and without internal blinds schedules (Fig. 33). Visual comfort improves dramatically for all cases with an external shading device ('view to the outside' in Fig. 34 & 35). Vertical fins as additional external shading elements added to OH100 and 5HL40 were shown to reduce glare in all cases, whereas, the electric lights use decreased only for the overhang (seen in Fig. 34 & 35). OH100+V100 in reference to OH100 in a scenario without internal blinds yielded higher lighting use (Fig. 33), however, due to reduction of glare, lighting with internal blinds operation was lower for OH100+V100.

Figure 33. Hours of electric lights operation (Stockholm, WWR 84 %).

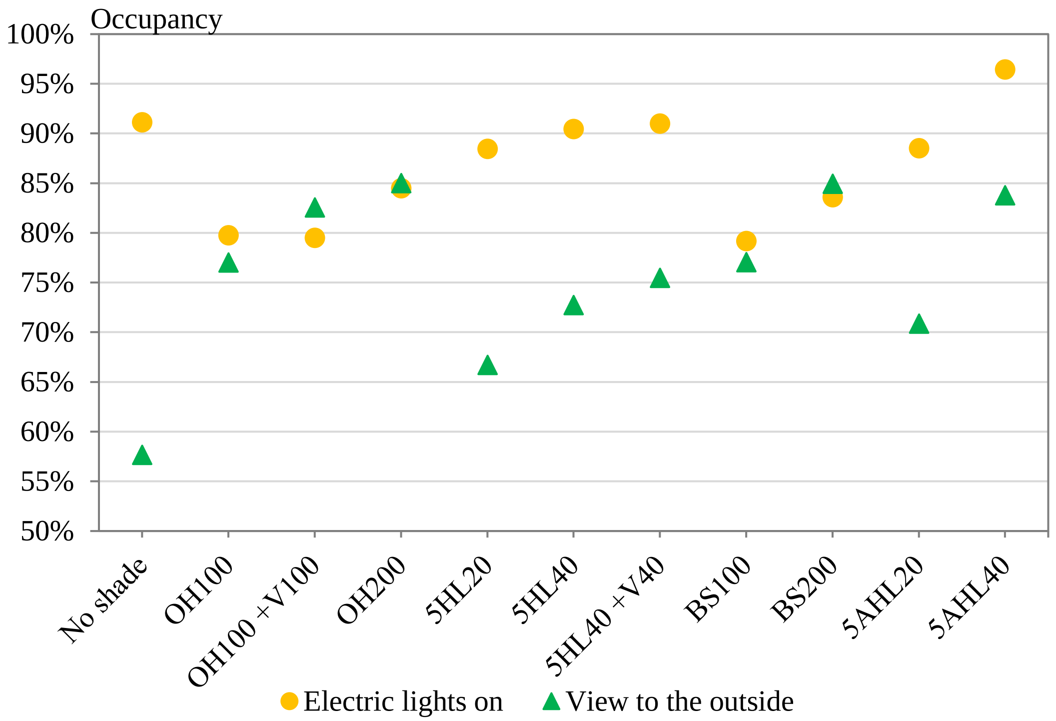


Figure 34. Percentage of annual occupancy time with lights-on and view-out (Stockholm, clear glass WWR 84 %).

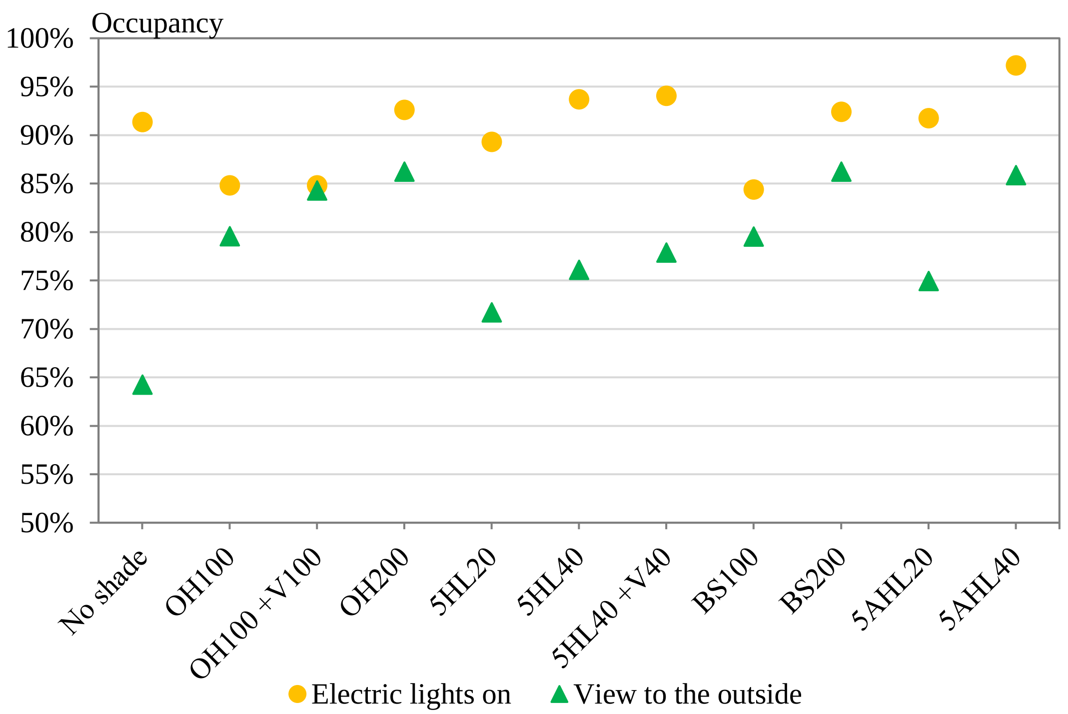


Figure 35. Percentage of annual occupancy time with lights-on and view-out (Stockholm, selective glass WWR 84 %).

Selective glass was found more energy-efficient when applied on a large size window. As it was previously shown, EUI reduction with selective glass for Stockholm WWR 44 % (section 4.2.1, Fig. 18) was 13 % in reference to clear glass for base case with internal blinds, whilst a large WWR (84 %) saw 28 % reduction of EUI (Fig. 36). Addition of vertical fins resulted in lower energy use only for OH100+V100 (Fig. 37). Larger size shading is more energy-efficient in case of clear glass window, but for selective glass, the differences between small and large shadings energy use results are too small.

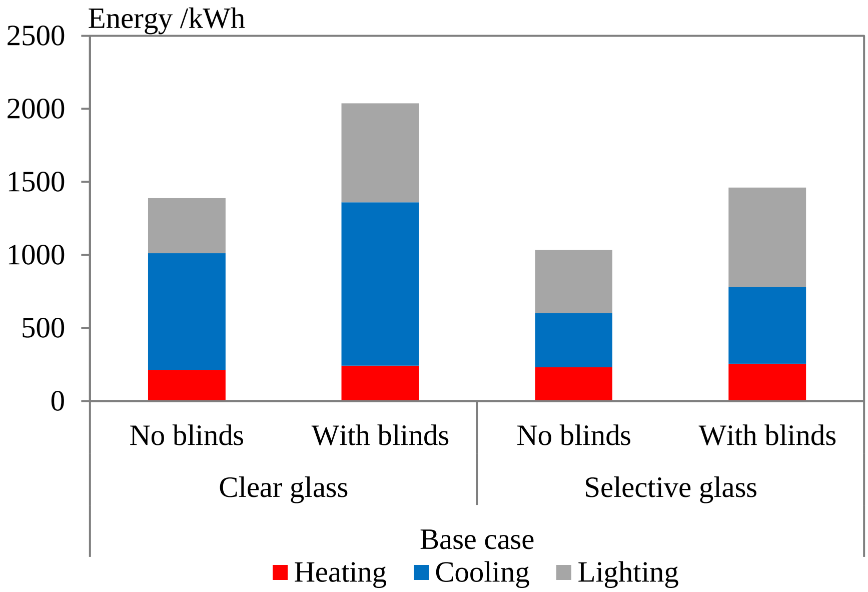


Figure 36. Energy use for base case (Stockholm, WWR 84%).

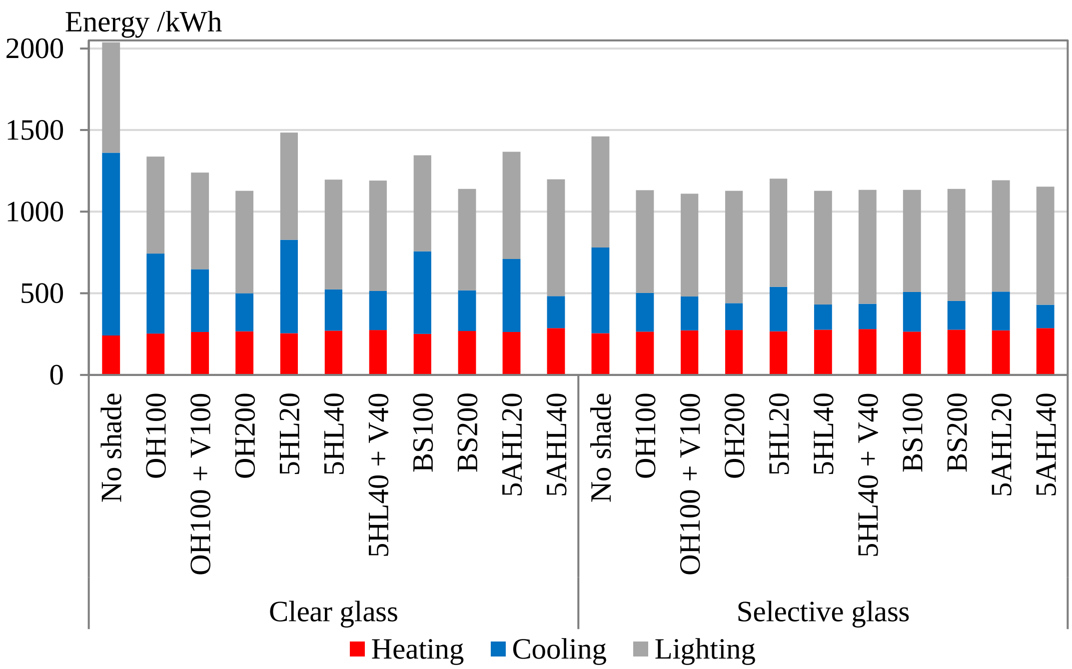


Figure 37. Energy use for studied cases with internal blinds (Stockholm, WWR 84 %).

Selective glass in combination with shadings proved effective in reduction of excessive solar heat gain (Fig. 38). The effect of that can be also seen in Figure 39, as the annual operative temperatures are largely reduced with selective glass. Again, operative temperatures stayed above 18 °C year round during occupancy for all cases.

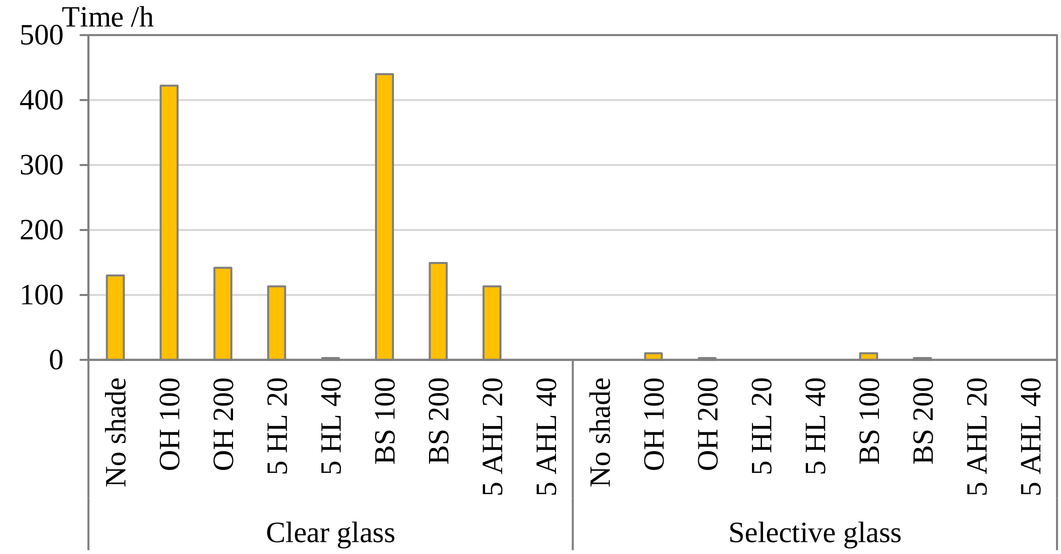


Figure 38. Number of hours in a year that exceed Miljöbyggnad Gold solar heat gain threshold of 22 W/m² (Stockholm, WWR 84%).

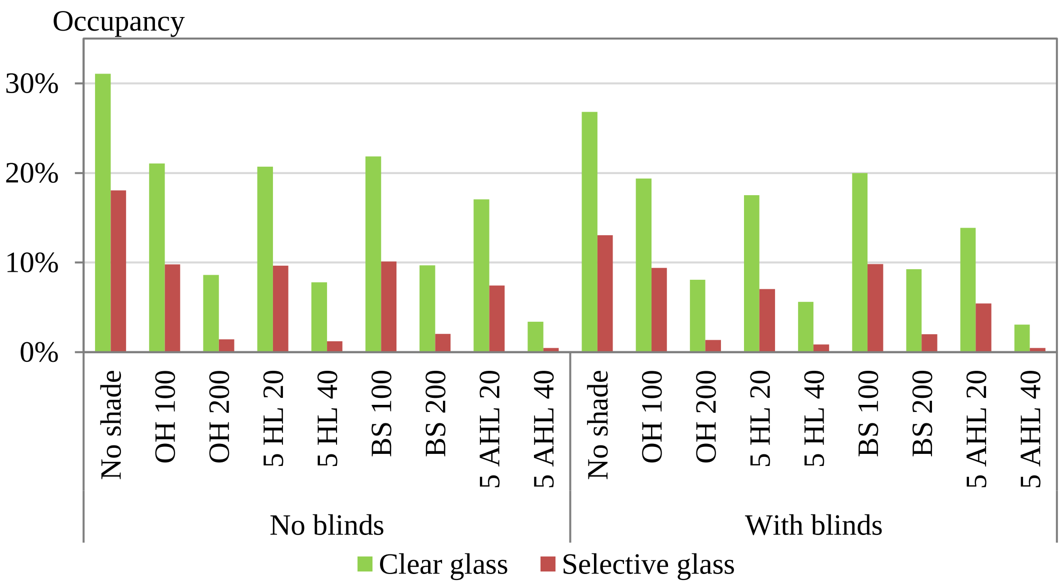


Figure 39. Part of occupancy time when operative temperatures exceed 25 °C (Stockholm, WWR 84 %).

External shadings ensure that the size of a cooling system can be significantly smaller, as seen from the chart in Figure 40, which shows corresponding cooling peak loads. Annual cooling demand can be substantially reduced for all studied cases when introducing more cool outdoor air by a ventilation system with an air-side economiser (Fig. 41).

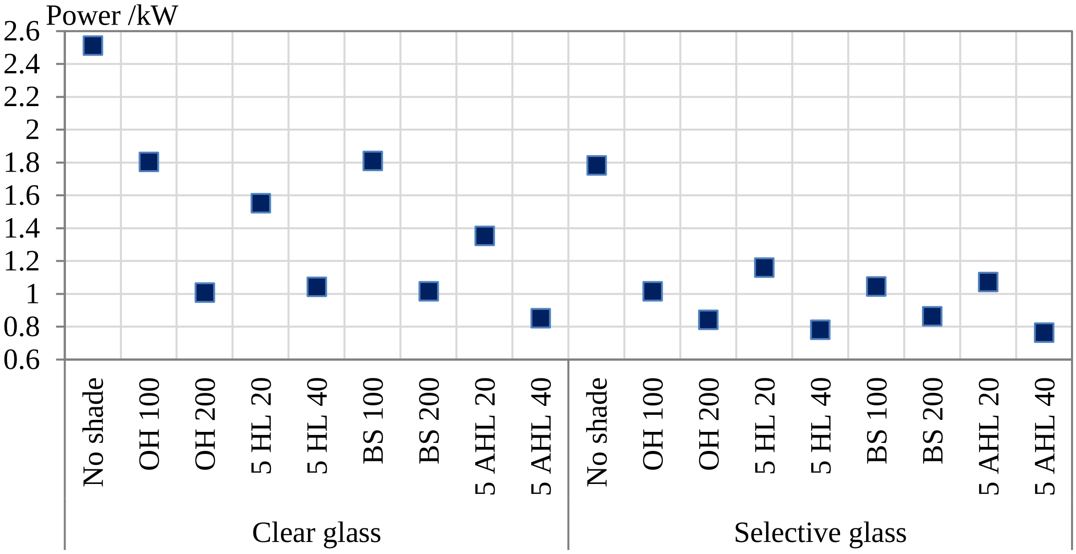


Figure 40. Cooling peak loads (Stockholm, WWR 84 %).

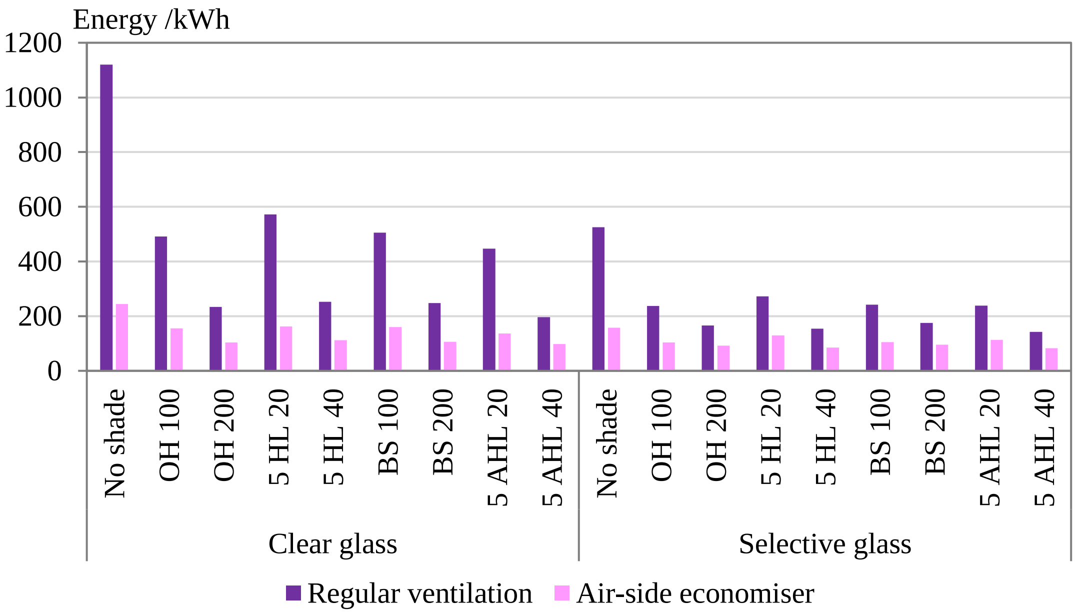


Figure 41. Annual cooling energy use (Stockholm, WWR 84 %).

4.2.4 Copenhagen WWR 84 %

In all of the presented study cases, as well as for the investigated large window size in Copenhagen, electric lighting use is largely amplified with the use of internal blinds, as can be noted from Figure 42, and selective glass increases the lighting use by as much as 10 % in relation to clear glass.

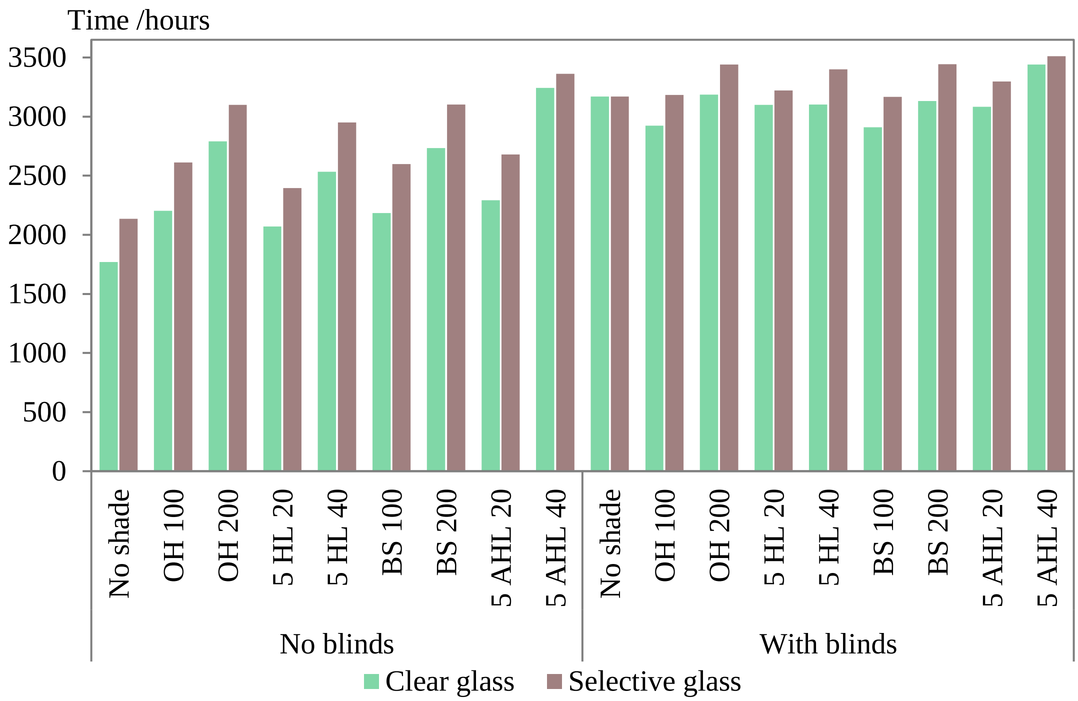


Figure 42. Hours of electric lights operation (Copenhagen, WWR 84 %).

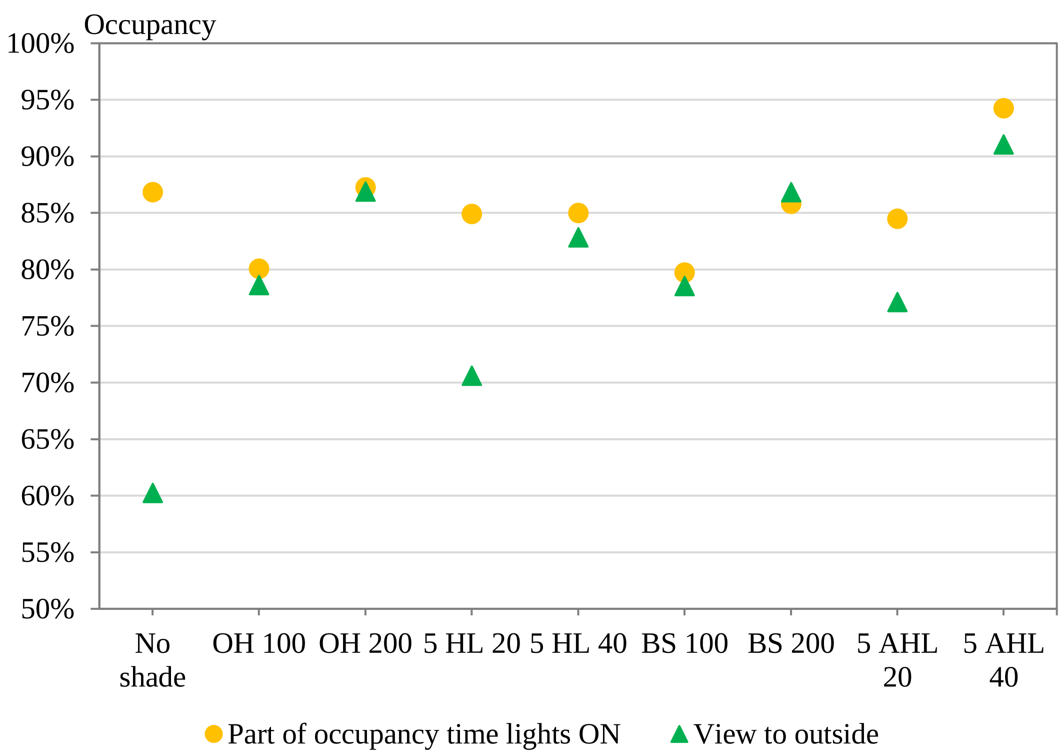


Figure 43. Percentage of annual occupancy time with lights-on and view-out (Copenhagen, clear glass WWR 84 %).

Seeing from Figure 43, smaller horizontal louvers external shading (5HL20) seems to create much worse glaring conditions than its larger equivalent (5HL40) having about the same use of electric lights, which accurately illustrates the complexity of glare and daylight in fenestration design. Selective glass, shown in Figure 44, increases time with view to the outside always by a smaller percentage than corresponding increase of electric lights use (or reduction of daylighting) in comparison to the respective cases of clear glass (Fig. 43), except for the base case without any external shading.

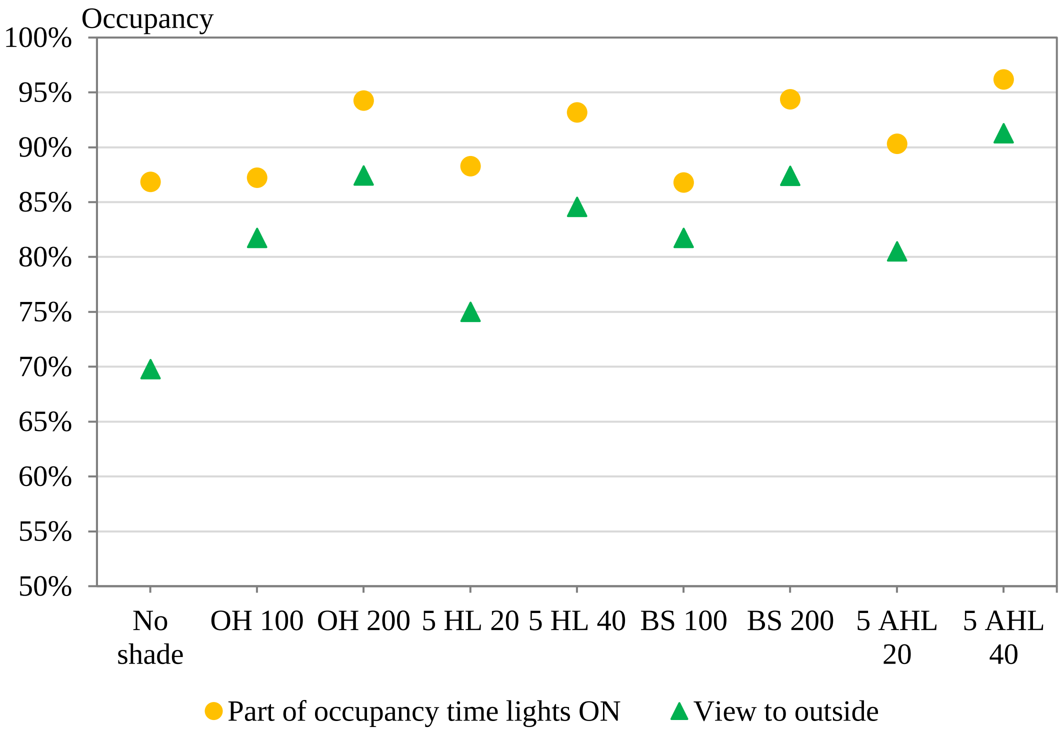


Figure 44. Percentage of annual occupancy time with lights-on and view-out (Copenhagen, selective glass WWR 84 %).

Figure 45 for Copenhagen WWR 84 % presents the same trends as in the previous charts of the same type in the afore-investigated cases, namely that for the base case selective glass is more energy-efficient, and that the inclusion of internal blinds operation to the annual energy simulations increases the resulting EUI. There are substantially greater differences in energy use between the studied cases with clear glass than with selective glass. For the latter, energy use is on roughly the same level, regardless of external shading solution (Fig. 46). As EUI with selective glass is generally lower, to reach a similar level of energy performance with clear glass, a larger size of external shading device is required.

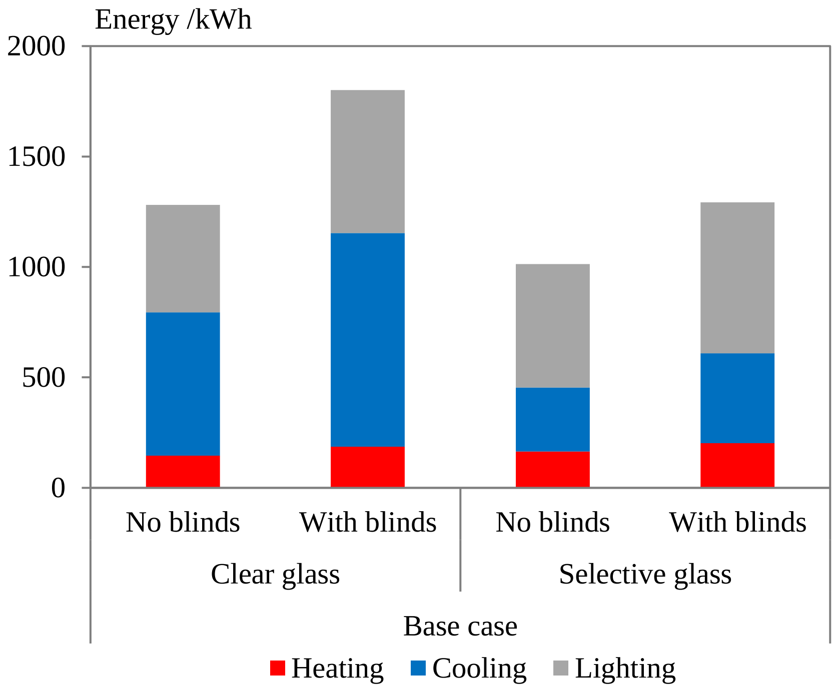


Figure 45. Energy use for base case (Copenhagen, WWR 84%).

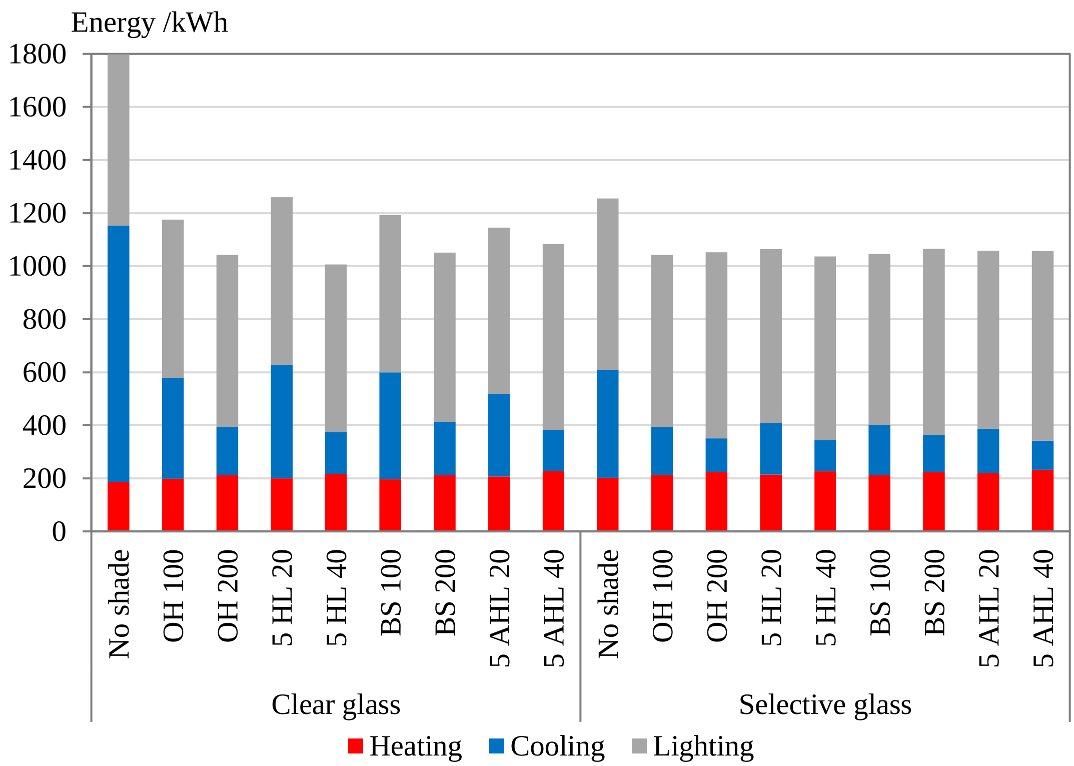


Figure 46. Energy use for studied cases with internal blinds (Copenhagen, WWR 84 %).

Regarding Miljöbyggnad solar heat gain gold criteria, it was not possible for clear glass cases to achieve the standard unlike the cases with selective glass (Fig. 47). Similarly, with clear glass there is a tendency for higher internal operative temperatures, as seen in Figure 48, and only large shading sizes can ensure better thermal comfort, while selective glass cases maintain the operative temperatures within a comfort zone for a greater part of the year. Predicted cooling peak loads and the deviations between the shading cases are presented in Figure 49, and generally exhibit the same tendencies as in the previous cases. Outdoor air cooling with air-side economiser on mechanical ventilation shows again great energy-saving potential in Copenhagen climate scenario (Fig. 50).

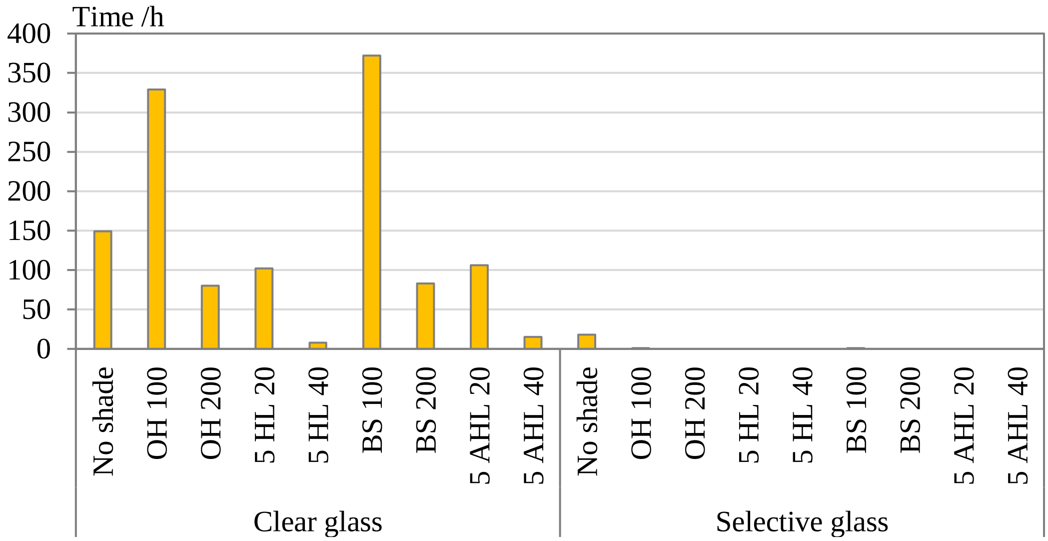


Figure 47. Number of hours in a year that exceed Miljöbyggnad Gold solar heat gain threshold of 22 W/m² (Copenhagen, WWR 84%).

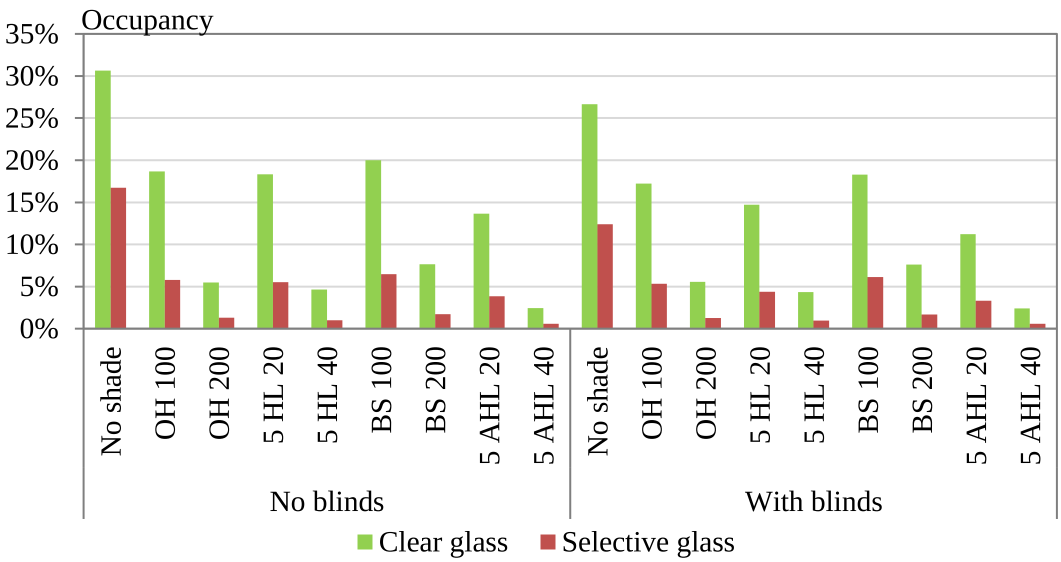


Figure 48. Part of occupancy time when operative temperatures exceed 25 °C (Copenhagen, WWR 84 %).

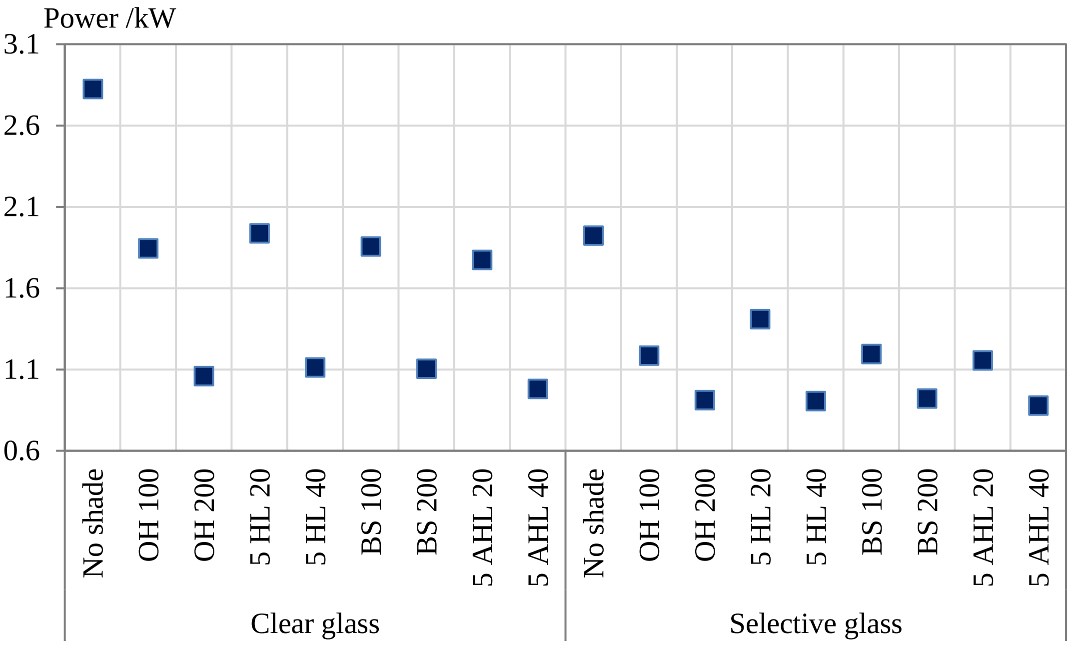


Figure 49. Cooling peak loads (Copenhagen, WWR 84 %).

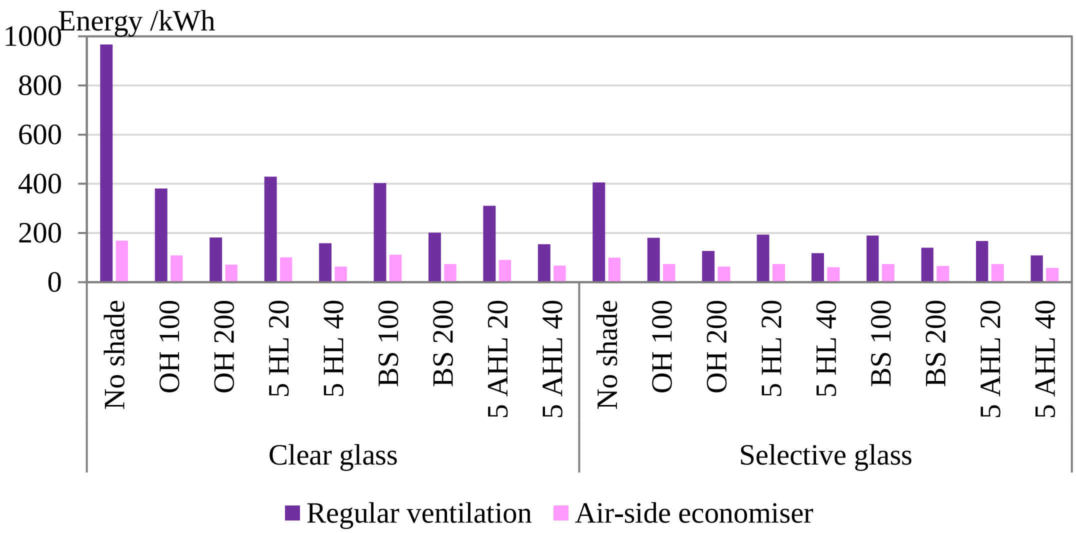


Figure 50. Annual cooling energy use (Copenhagen, WWR 84 %)

4.3 Performance predictions

4.3.1 Reference days

Climate day types and noon solar angle distribution over a year in Stockholm can be seen in Figure 51. Selected solar angle range boundary of 30° happened to coincide with Spring and Autumn equinoxes for Stockholm climate. Reference days are marked and labelled. Figures 53, 54, 56, 59 illustrate hourly energy and temperature profiles for selected reference days A, B, C, D without accounting for the operation of internal blinds, while Figures 52, 55, 57, 58 express the total resulting energy use for those respective days.

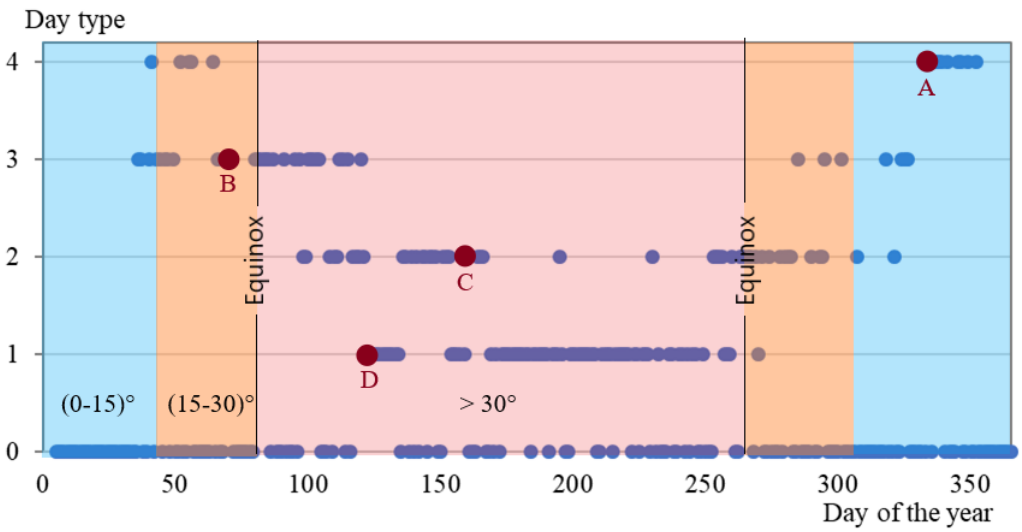


Figure 51. Climate day types over a year period in Stockholm, with noon solar altitudes, and selected reference days (A, B, C, D).

Reference day A (RD-A) is characterised by solar angles lower than 15°. Theoretically, in order to shade all direct solar radiation of altitude 15° from falling on a window of height ‘h’, overhang offset length would have to be 3.7 times larger than ‘h’. However, from base case results in Figure 52, it can be seen that RD-A is a heating day, therefore, solar radiation is an energy benefit. Expectedly, solar gain reduction with shadings is not substantial (Fig. 53), and lighting need is unaffected. Overall EUI increased by 5 %. Considering glare (Table 7), RD-A experiences 7 hours of disturbing (or worse) glare and the external shading devices do not help mitigate the issue.

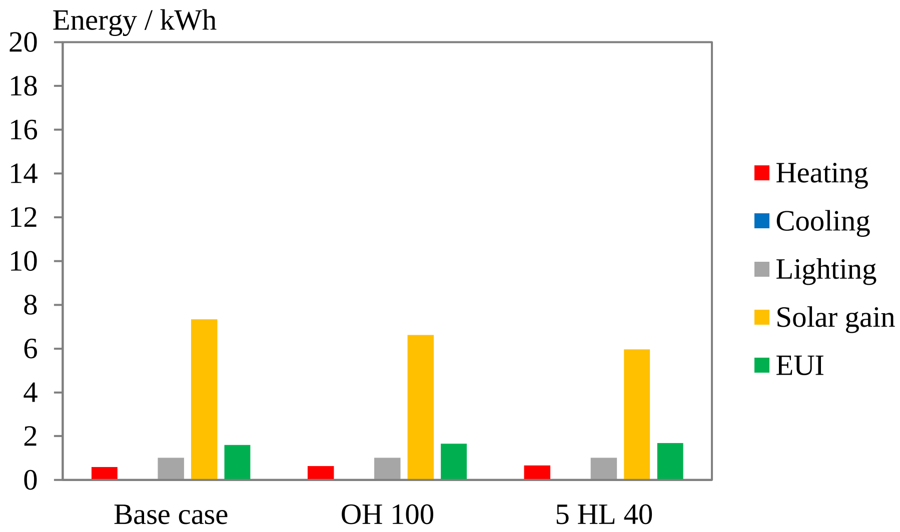


Figure 52. Energy use results for reference day A (without blinds).

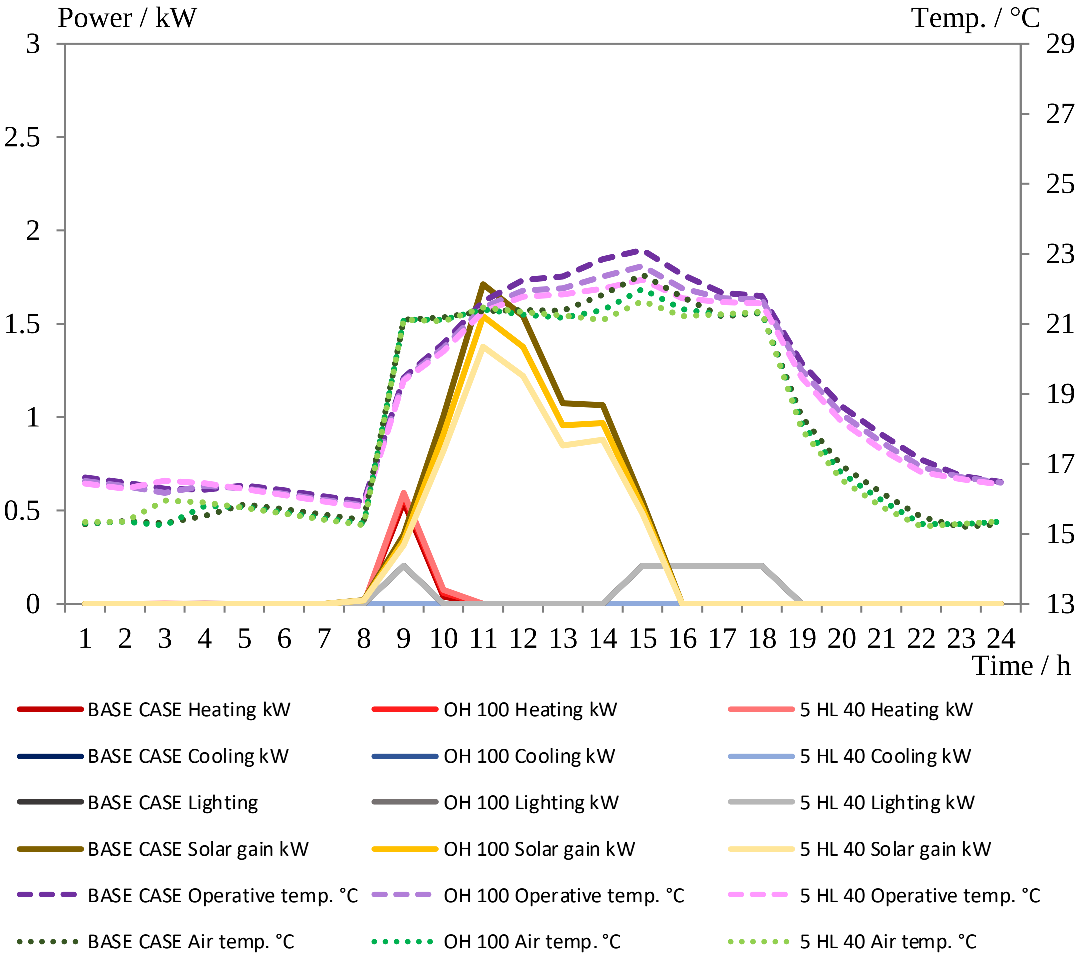


Figure 53. Energy and temperature profile for reference day A.

Reference day B (RD-B), with solar altitudes characteristic for spring and autumn, was both a heating and a cooling day, and it recorded up to 43 % decline in solar heat gain with addition of shadings that, for the bigger shading geometry, eliminated the cooling need entirely (Fig. 54). Significant drop in operative temperatures can also be observed that indicates higher thermal comfort. There are 8 glare hours of the base case scenario, and shading help reduce the problem (Table 7). Resulting lighting use is similar in all cases either with or without internal blinds. External shadings reduced the EUI by up to 74 % (Fig. 55).

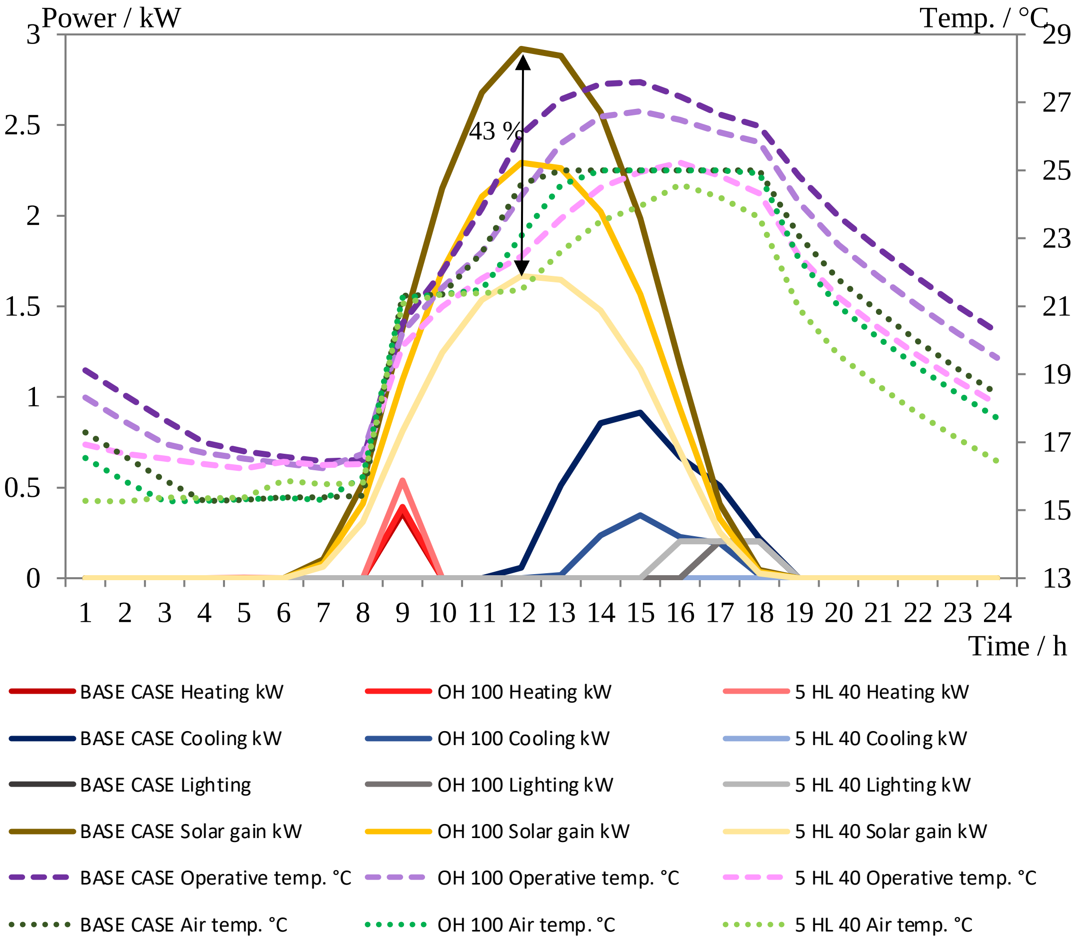


Figure 54. Energy and temperature profile for reference day B.

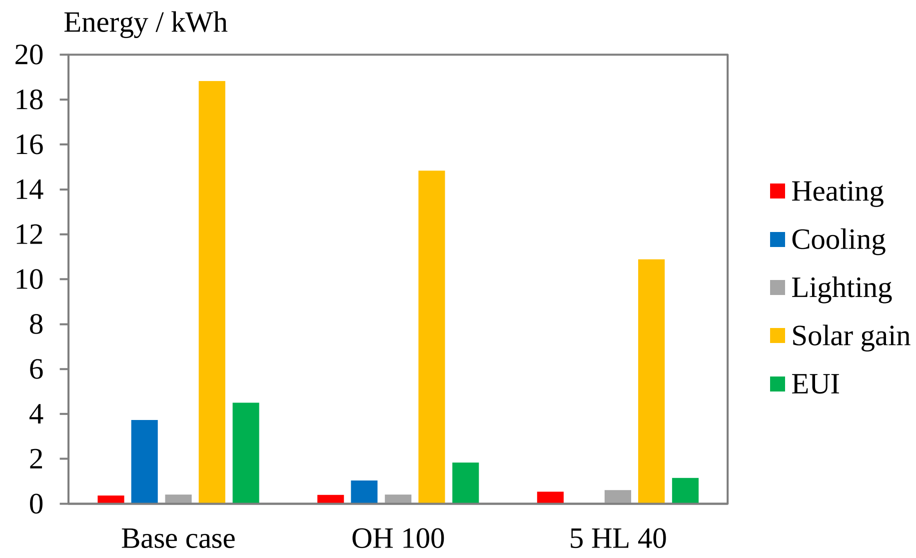


Figure 55. Energy use results for reference day B (without blinds).

Reference day C (RD-C) is a day in June with highest solar angles from all selected RDs, and it can be seen from the profile that the shadings are extremely effective in reducing solar heat gain (Fig. 56) – up to 85 % reduction at one hour. Lighting use increased significantly with external shadings but glare was completely eradicated (Table 7). In general, selected RD-C benefits from an external shading device, but EUI reduction from small to large size shading is less due to increase in lighting (Fig. 57).

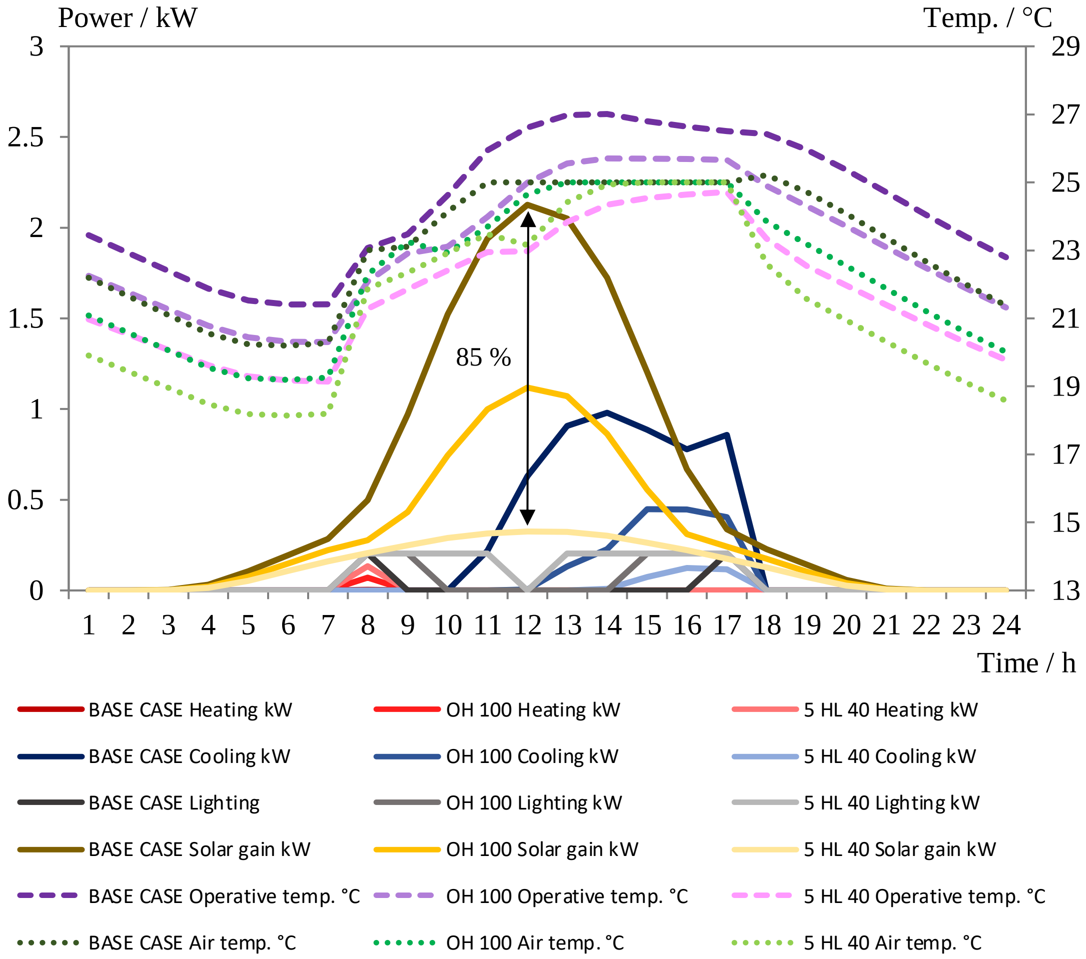


Figure 56. Energy and temperature profile for reference day C.

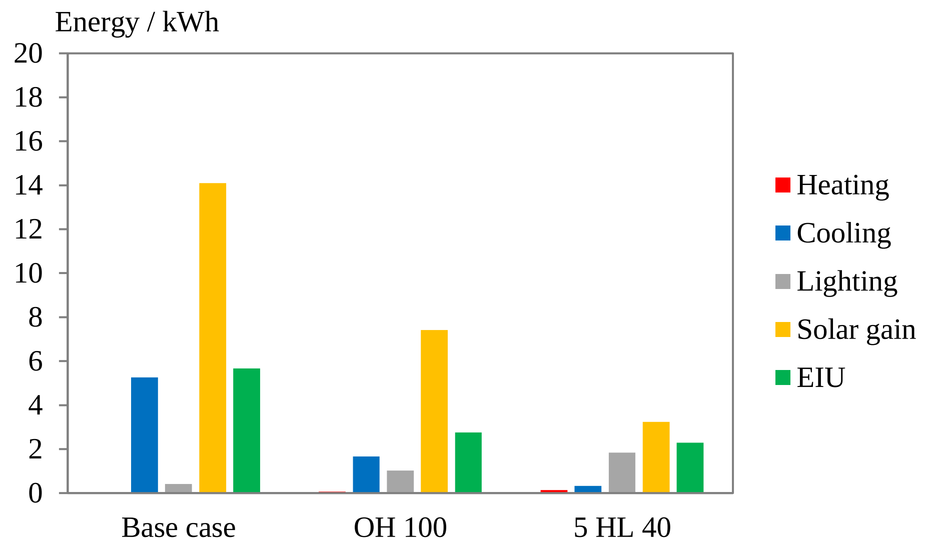


Figure 57. Energy use results for reference day C (without blinds).

On a very warm and sunny day as reference day D (RD-D), the operative temperature reaches almost up to 28 °C without solar shadings, but can be reduced down to a comfortable level with solar shadings (Fig. 59). Just like in RD-C, the lighting need increased for shading cases, however, while glare was successfully mitigated with an OH type of shading, it was not as effectively reduced with a larger HL type (Table 7). Overall EUI reduction was quite substantial (Fig. 58).

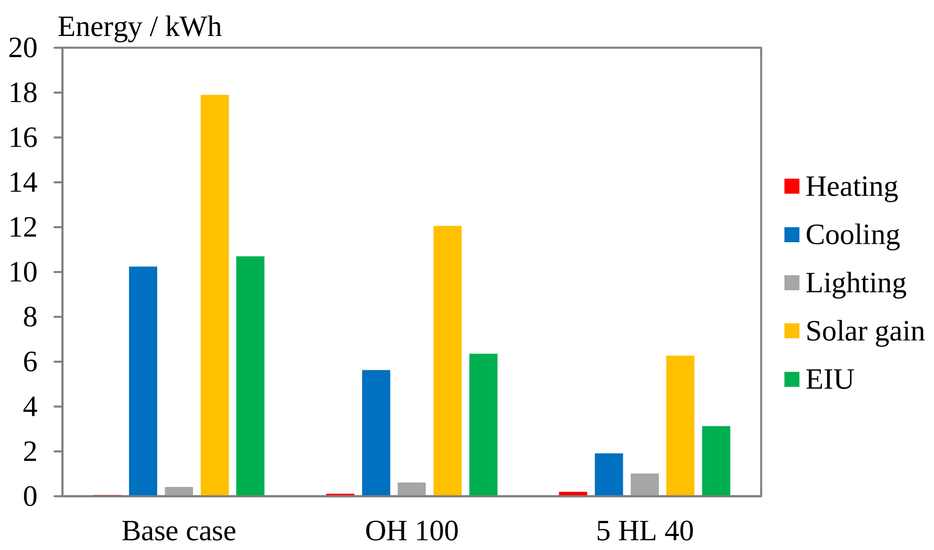


Figure 58. Energy use results for reference day D (without blinds).

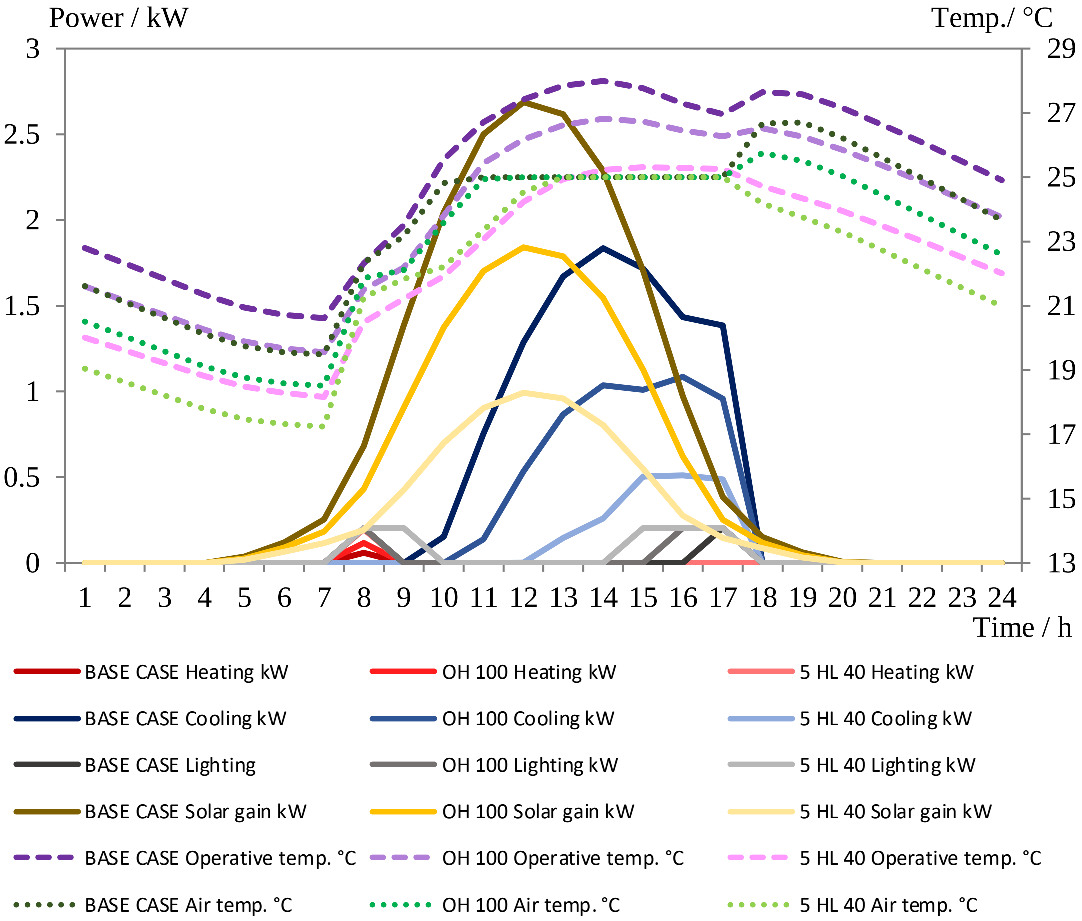


Figure 59. Energy and temperature profile for reference day D.

Table 7 presents the number of hours of electric lights operation and glare that each reference day experiences. It should be read in the following way, e.g. base case on RD-B requires 2 hours of electric lighting due to insufficient daylight level at the sensor point, plus 7 extra hours with lights on due to glare induces blinds operation, however, blinds are active for 8 hours that day, which also means that only one hour of glare was concurrent to insufficient daylight, and the rest (7 hours) provided enough daylighting.

Table 7. Electric lighting duration hours: due to insufficient daylight + extra due to blinds down, and internal blinds operation hours due to glare.

	Base case		OH 100		5 HL 40	
	Lights /h	Blinds /h	Lights /h	Blinds /h	Lights /h	Blinds /h
A	5 + 5	7	5 + 5	7	5 + 5	7
B	2 + 7	8	2 + 7	7	3 + 5	6
C	2 + 7	7	5 + 0	0	9 + 0	0
D	2 + 7	8	3 + 2	2	5 + 4	6

4.3.2 Shading benefit index

4.3.2.1 External shading

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Stockholm weather data based ESBI chart in Figure 60 displays non-negative values obtained from Equation (1) for hours when solar rays fall onto the window geometry. The chart exhibits similar intensity patterns as a simulated solar heat gain reduction chart in Figure 61, which was achieved by an OH100 external shading device compared to the base case results for Stockholm clear glass WWR 84 %. A high correlation of peaks and shapes in the colour displays between the two charts can be initially assessed by vision, and it is apparent that the high scale colour patches look alike. At this point of the prediction methods development, comparative visual assessment of the charts to find correlation of patterns is the primary validation method. Previously mentioned in section 3.3.2.1, ESBI values higher than 1 are considered to indicate periods in a year, during which a solar shading device is expected to bring significant benefits to the building performance. 'Benefit' in this case is used to describe solar heat gain reduction. The exact translation of ESBI scale is still unknown.

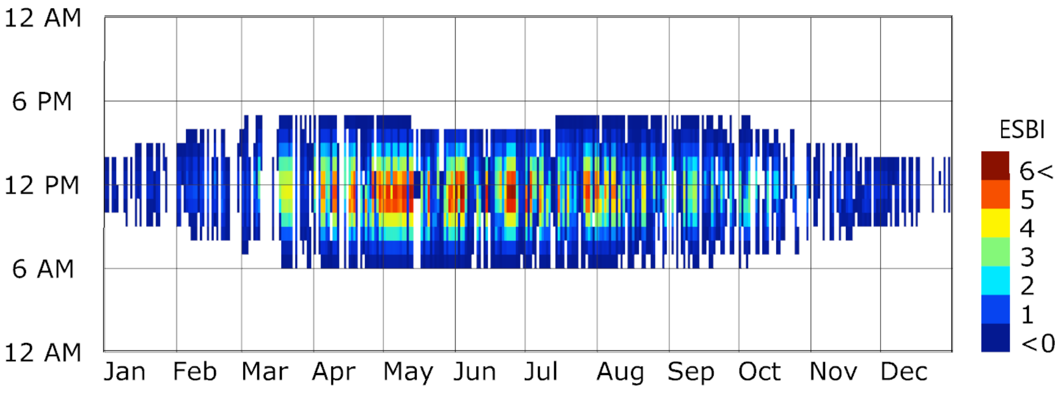

Figure 60. ESBI for Stockholm climate.

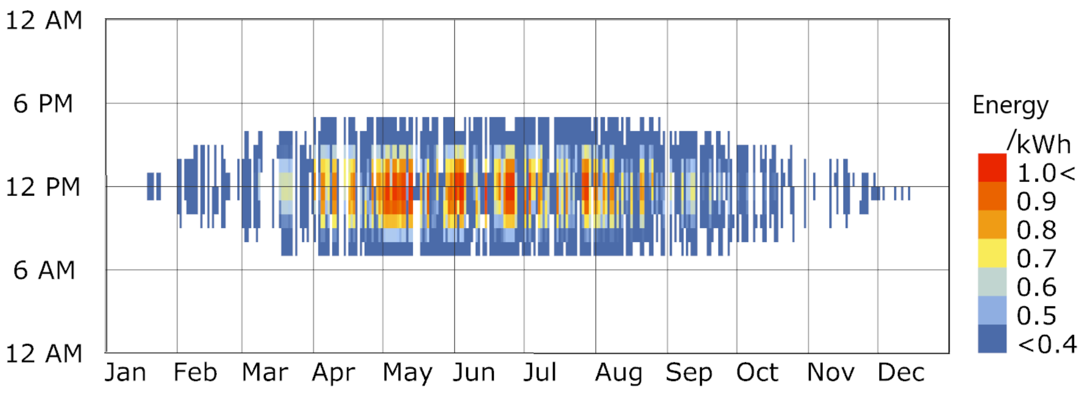

Figure 61. Solar heat gain reduction from base case without shading to OH100 (Stockholm, clear glass WWR 84 %).

Results of ESBI.vent for Stockholm can be seen in Figure 62. Comparing the chart to the previous ESBI in Figure 60, immediate differences in colour intensity can be noticed, including a big change for spring months (marked as ‘A’ in Fig. 62), where lowered indices indicate that substantial cooling reductions can be achieved by outdoor air cooling. Low outdoor temperatures for that period, when used in Equation (2), they contributed to lowering of the ESBI.vent values for those hours. Similarly, a chart area in autumn – marked with ‘B’, shows potential for free cooling, as the values in that part are of lower scale than the previous ESBI results. High values of ESBI.vent, therefore, indicate the most critical periods, in which overheating will likely occur, regardless of outdoor air ventilation strategy, so benefits of external shading during these periods can still be noted. As can be seen from Figure 63, those periods in ESBI.vent (Fig. 62) are corresponding to cooling loads reduction by OH100 in reference to the base case, simulated for Stockholm, clear glass WWR 84 %, with an air-side economiser as a free cooling strategy. Comparing the two charts, it can be seen that the peaks of cooling reduction achieved by an external overhang are concurrent with high values of ESBI.vent.

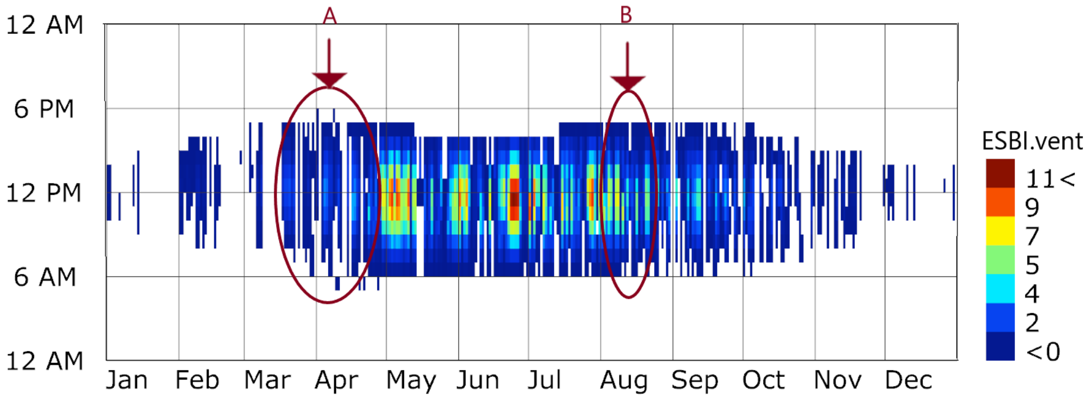

Figure 62. ESBI.vent for Stockholm climate.

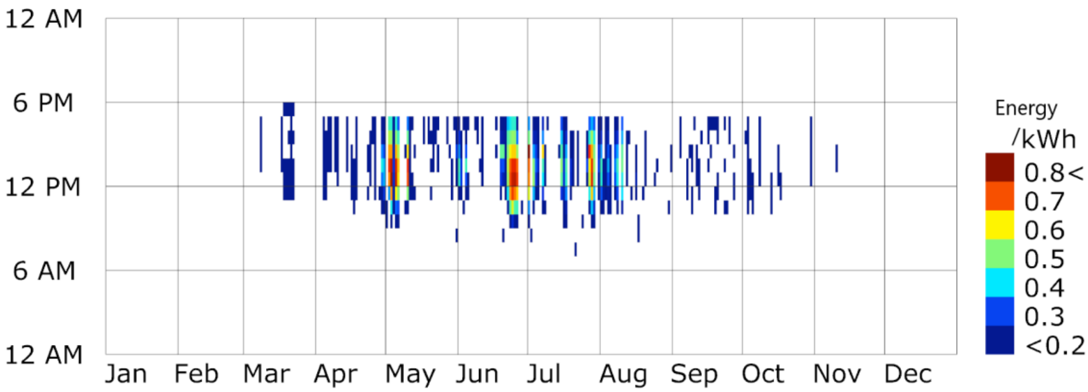

Figure 63. Cooling loads reduction from base case without external shading to OH100 (Stockholm, clear glass WWR 84 %, with air-side economiser).

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It can be noted that the chart of ESBI for Copenhagen (Fig. 64) displays more colour of the top scale (dark red) compared to Stockholm, which may due to higher solar angles that are easily shaded so the benefit of external shading is eminent. It can be also observed that summer weather in Copenhagen area is in general less sunny than in Stockholm by looking at the intermittent dark-blue vertical intervals of the annual ESBI chart. In fact, the number of hours in the year with ESBI larger than 5 was 91 for Stockholm and 72 for Copenhagen, which validates the former hypothesis that Copenhagen is less sunny. Copenhagen ESBI chart resembles the patterns of a simulated annual chart displaying solar heat gain reduction achieved by OH100 in reference to the base case for Copenhagen clear glass WWR 84 % as seen from Figure 65. There is again a high visual correlation between the predicted and simulated values.

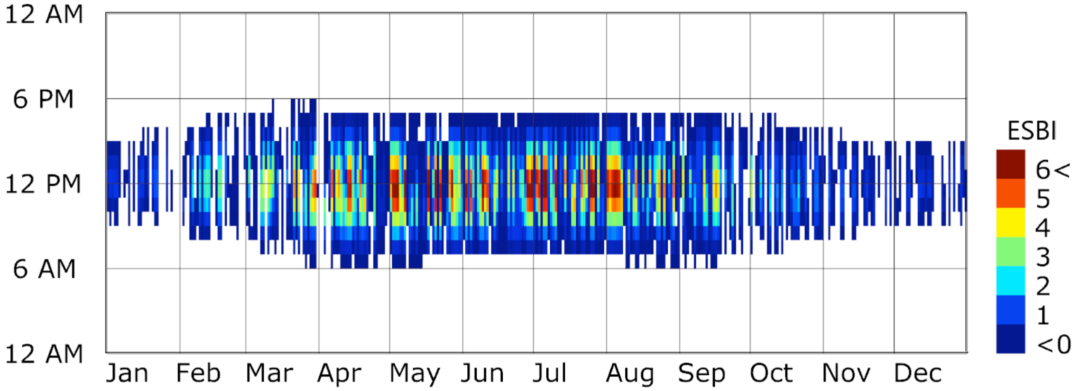

Figure 64. ESBI for Copenhagen climate.

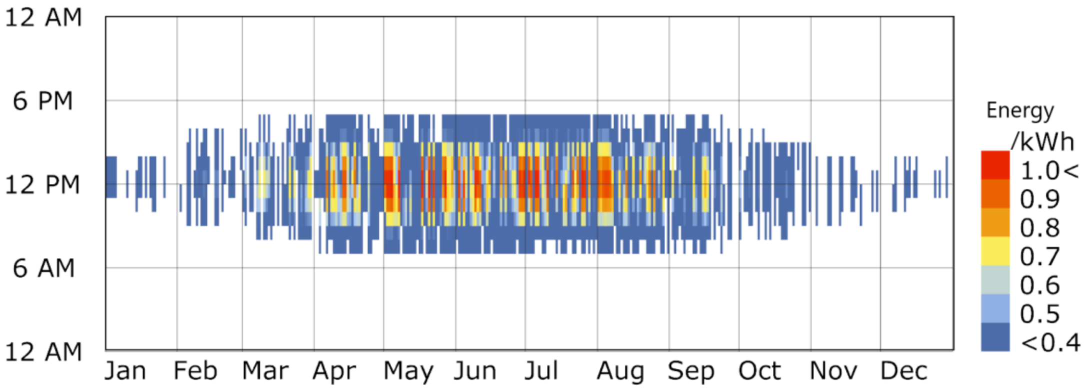

Figure 65. Solar heat gain reduction from base case without shading to OH100 (Copenhagen, clear glass WWR 84 %).

ESBI.vent chart for Copenhagen (Fig. 66) shows many more regions with lower scale values, when compared to the initial ESBI chart in Figure 64. These periods were marked with 'A', 'B', and 'C' in Figure 66, and represent times in a year when an outdoor air cooling strategy can potentially be beneficial. The abundance of reduced external shading benefit (areas that turned dark-blue) in ESBI.vent suggests suitably cool outdoor air temperatures for free cooling in Copenhagen. Peaks of ESBI.vent for Copenhagen also correspond directly with periods of highest yearly cooling reduction by OH100 external shading compared to the base case results, simulated with air-side economiser added ventilation (Fig. 67). It suggests that the predicted benefit of a shading is matching the simulated energy savings with a shading device.

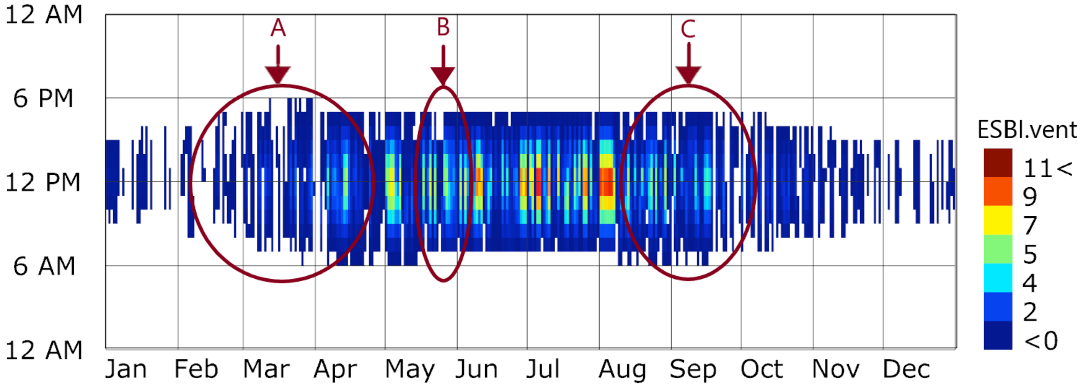

Figure 66. ESBI.vent for Copenhagen climate.

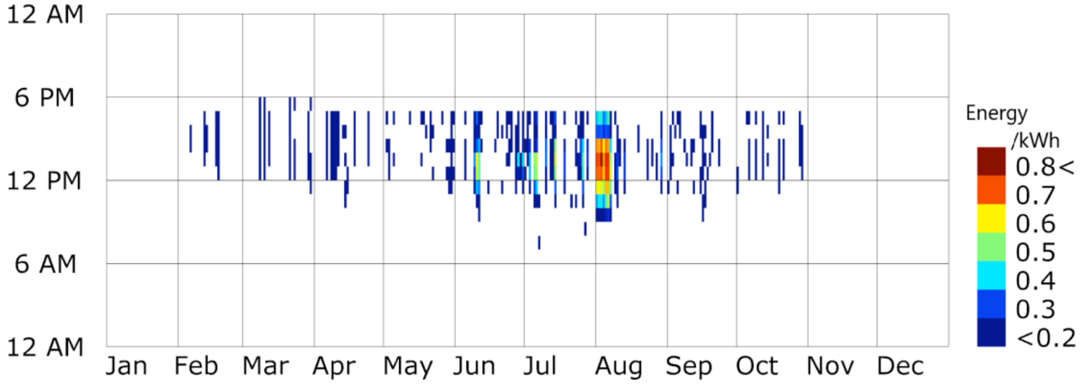

Figure 67. Cooling loads reduction from base case with no external shading to OH100 (Copenhagen, clear glass WWR 84 %, with air-side economiser).

Comparing ESBI.vent charts (Fig. 62 & 66) for the two climates, it can be noticed that Copenhagen climate is colder in summertime, which provides a greater opportunity for free cooling. There are 153 hours of ESBI.vent above 5 in Stockholm annually, and 129 in Copenhagen

4.3.2.2 Internal shading

STOCKHOLM

ISBI was initially calculated from two different equations – one that uses DSR in a basic form, and the second one that uses a square root of DSR (Eq. 3). The difference between ISBI charts for Stockholm with DSR and with $\sqrt{DSR}$ can be seen from Figures 68 and 69. It can be noted that in Figure 68 that the ISBI without square-rooting of the DSR is more monotonous in its predominant colours and that the high-scale ISBI values are stretched vertically (along the y-axis) suggesting long daily occurrence of visual discomfort. On the other hand, the chart visualisation of ISBI with $\sqrt{DSR}$ (Fig. 69) is more concentrated along the 12 PM horizontal line, and the morning or late afternoon hours are not in the high scale range. The validation method (explained in section 3.3.2, Fig. 7) aimed to determine which equation approach is closer to the simulated DGP chart values for a large window with clear glass, as seen in Figure 71. It resulted in total sum of 817 for ISBI with DSR and 596 for ISBI with $\sqrt{DSR}$, which suggests that the square rooted solar radiation is a better representation for ISBI in regard to the simulated DGP case, due to a lower total sum, therefore, further on the analysis continued with this approach. Square-rooting of DSR values tampers the impact of the intensity of solar radiation, and puts more stress towards the low solar angles, which may be concurrent with low radiation values but are most critical to glare, whereas the high solar angles might be of higher power but are not as impactful when considering glare. Figures 70 and 72 show examples of simulated DGP charts for other window cases in Stockholm climate.

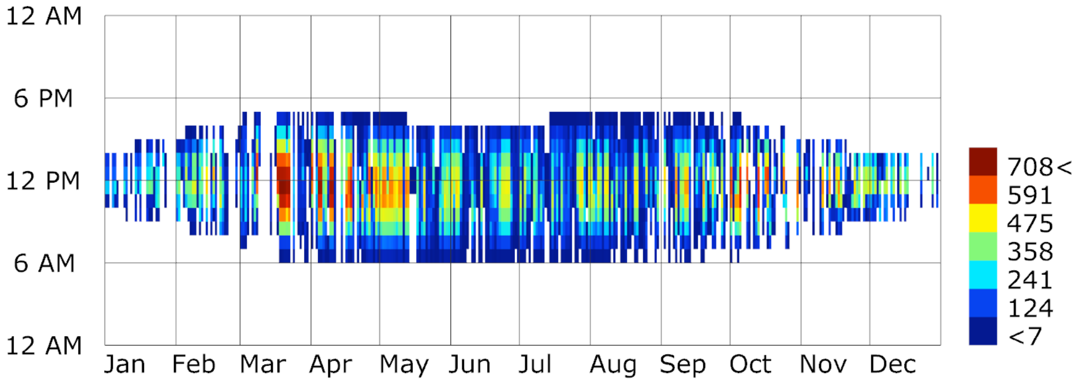

Figure 68. ISBI for Stockholm climate – without square-rooting DSR.

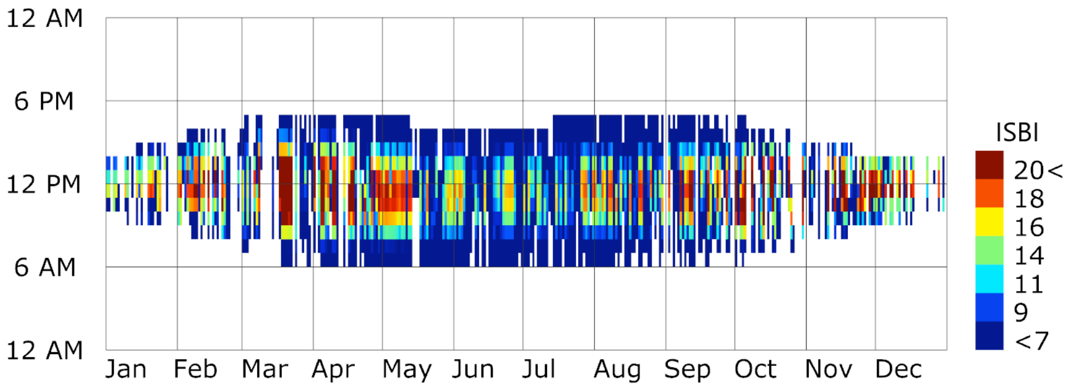

Figure 69. ISBI for Stockholm climate.

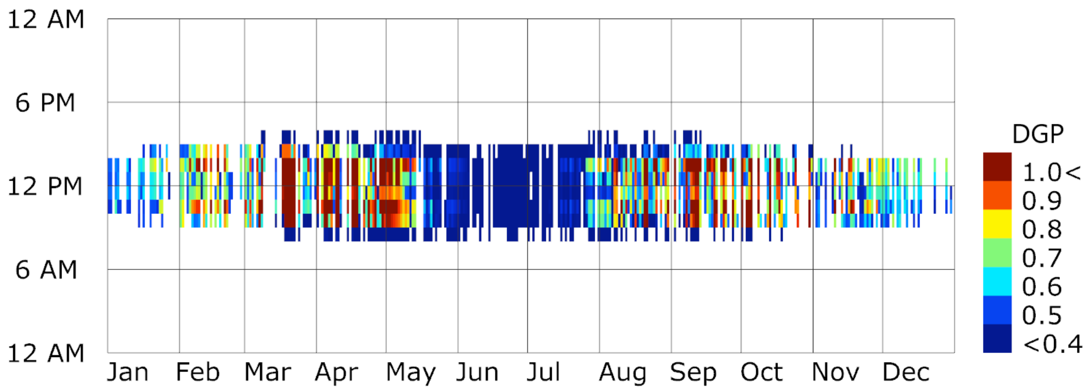

Figure 70. Combined DGP above 0.3 for east & west, Stockholm, clear glass WWR 44 %, no external shading.

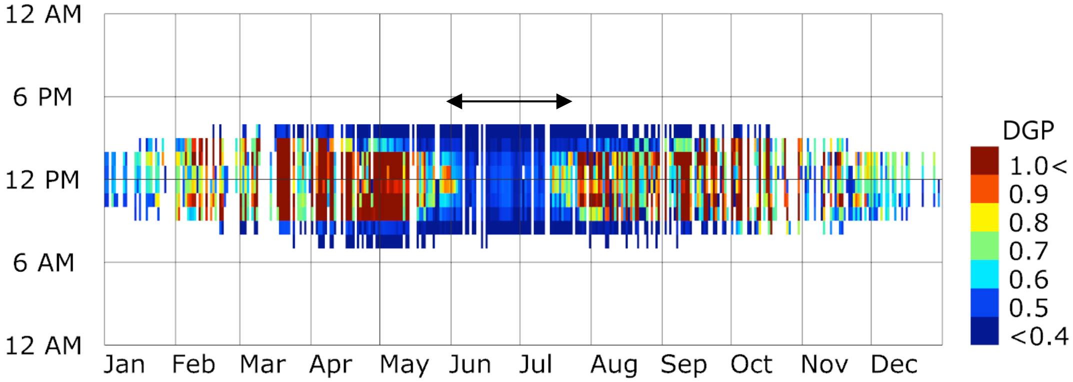

Figure 71. Combined DGP above 0.3 for east & west, Stockholm, clear glass WWR 84 %, no external shading.

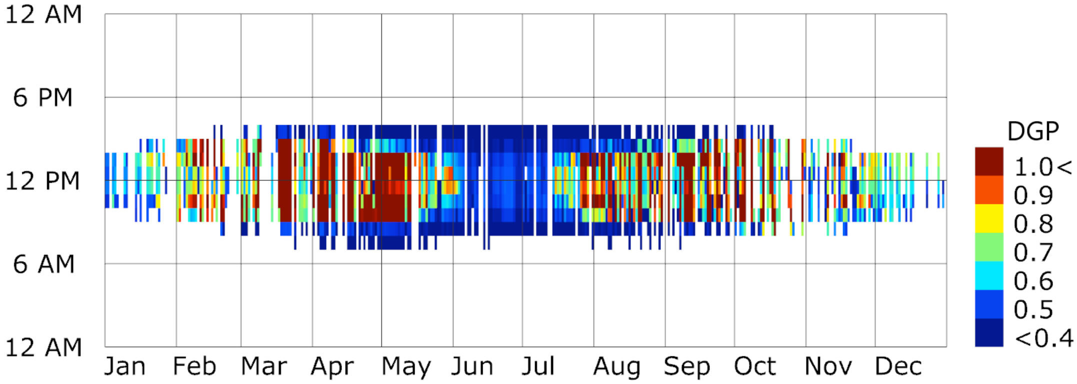

Figure 72. Combined DGP above 0.3 for east & west, Stockholm, selective glass WWR 84 %, no external shading.

Comparing Figures 70-72, which represent selected DGP results, it can be noted that for a large window (WWR 84 %) and clear glass case (Fig. 71), high summer period (marked with a line) exhibits higher DGP values than e.g. small clear galss window (Fig. 70). Further on, looking at Figure 73, which displays annual internal blinds schedule for the same window case (large, clear glass), it can be seen in that disturbing glare indeed occurs during the entire high summer.

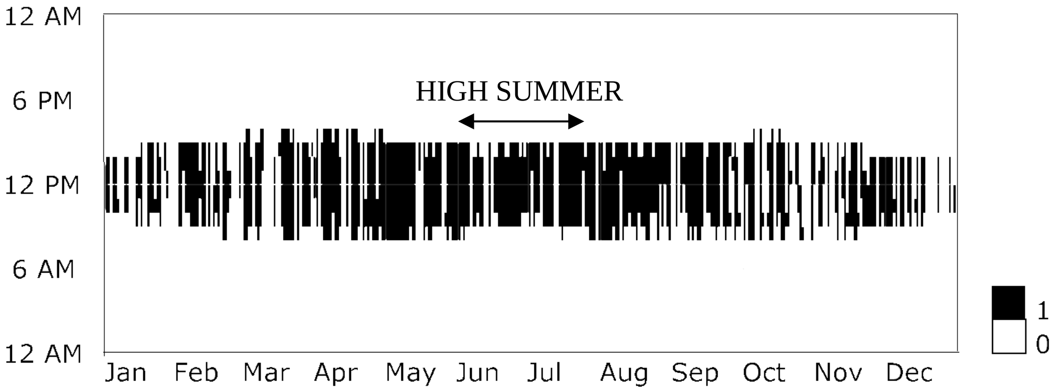

Figure 73. Internal blinds schedule (1 = ON, for DGP > 0.4) for Stockholm, clear glass WWR 84 %, no external shading.

Figure 74 illustrates the same ISBI as in Figure 69 but only values above a selected threshold of ISBI = 7, which might refer to hours with high risk of glare, hence significant benefit from an internal shading device can be expected. Resemblance of the plot coverage and shape of internal blinds schedule and ISBI charts in Figures 73 and 74 may suggest that the critical point in the ISBI scale, above which disturbing glare is highly possible, can be close to ISBI value of 7 and higher. If those ISBI values from Figure 74 were converted into an internal binds schedule, 89 % of the occupancy hours in the year would match the internal blinds schedule from Figure 73. The unmatching 11 % consisted of 330 hours of blinds operation from simulated DGP (from Fig. 73) that were concurrent with ISBI of less than 7, and 61 hours with ISBI above 7 but no blinds operation according to the simulated DGP-based schedule. The arithmetic mean of ISBI values of the aforementioned 330 unmatching hours was equal to 5.5, while 75 % of these values were larger than 4.7.

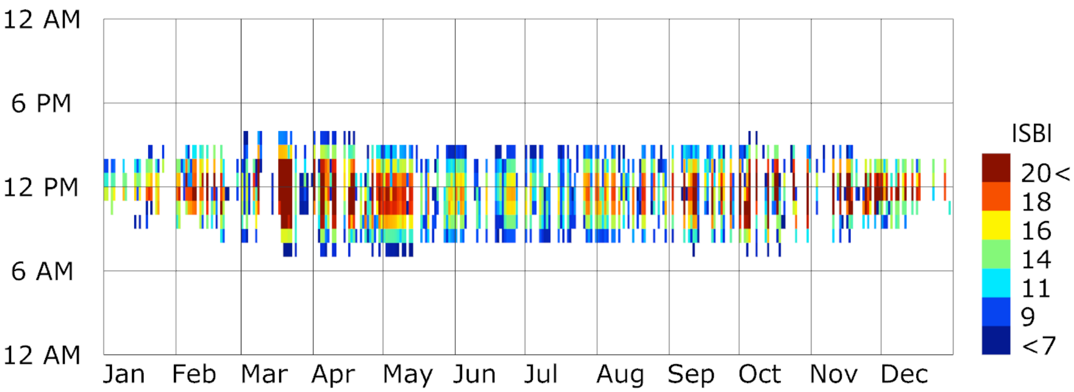

Figure 74. ISBI for Stockholm climate – only values above 7.

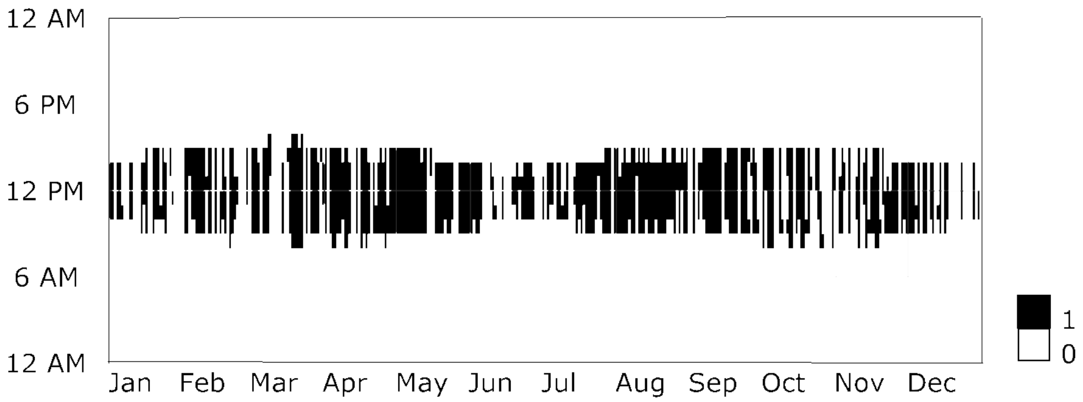

Figure 75. Internal blinds schedule (1 = ON, for DGP > 0.4) for Stockholm, selective glass WWR 84 %, no external shading.

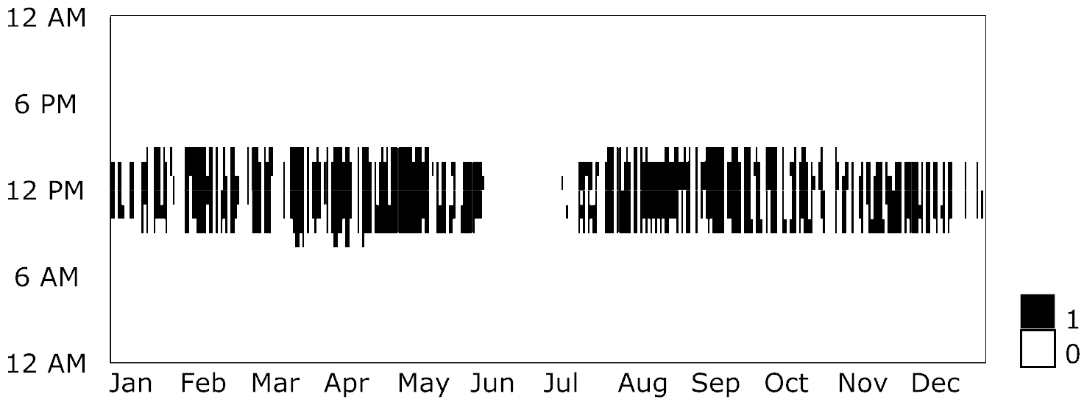

Figure 76. Internal blinds schedule (1 = ON, for DGP > 0.4) for Stockholm, clear glass WWR 44 %, no external shading.

In case of a smaller window (WWR 44 %) or selective glass, the schedules for internal blinds (Fig. 75 and 76) show less frequent blinds operation in high summer. Figures 77 and 78 present results of a modified version of the ISBI equation (see section 3.3.2.2) – ISBI.mod (Eq. 4). The chart of ISBI.mod displays lower values for high summer compared to ISBI, which can be seen from Figure 78 that displays ISBI.mod values above 7. The high summer plot fill is much thinner than in the previous ISBI chart in Figure 74, which suggests less likely benefit from internal shading during that time. This change in ISBI equation provided a chart as an outcome that is a better representation of the actual simulated disturbing glare for smaller window or selective glass, as seen from schedules in Figures 75 and 76, since less glare in high summer period was observed for those cases.

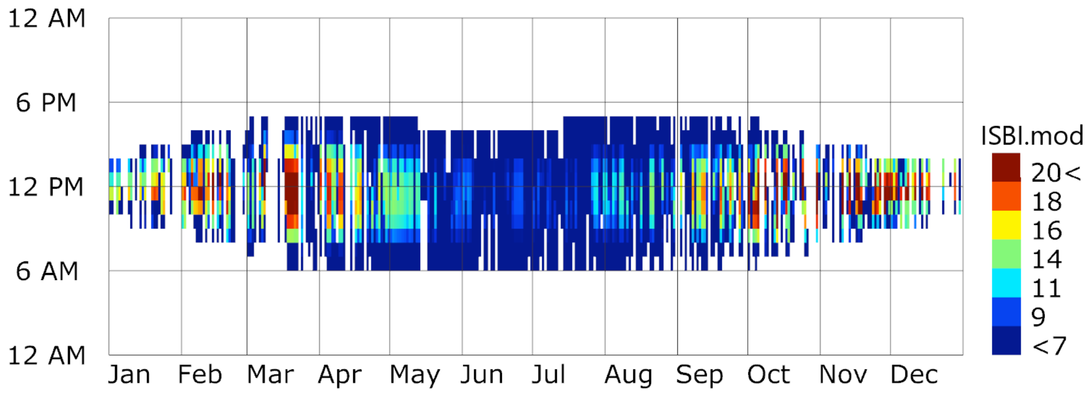

Figure 77. ISBI.mod with sine of azimuth to the power of 2 for Stockholm climate.

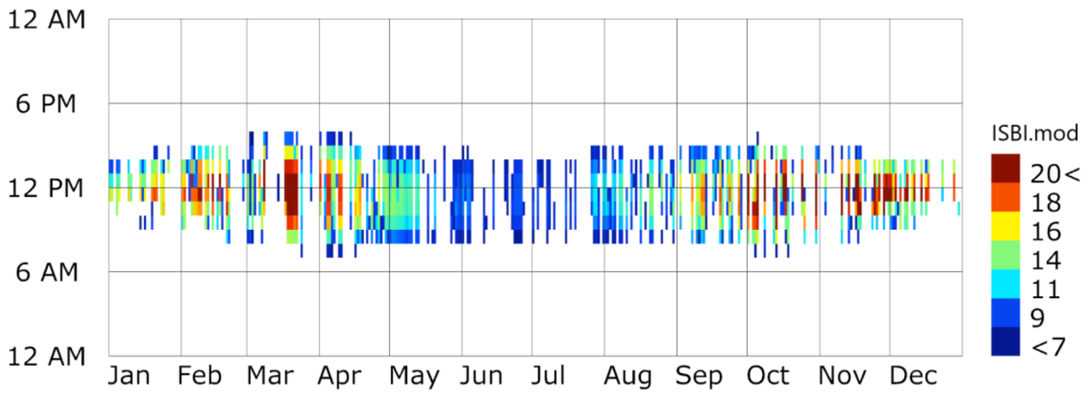

Figure 78. ISBI.mod for Stockholm climate – only values above 7.

Following that thought, ISBI.mod could be also used to assess the need for internal blinds when an external shading device such as an overhang is applied. It was noted that ISBI.mod values above 11 show similar occurrence patterns in the annual chart (Fig. 79) as the internal blinds schedule for a large clear glass window with OH100 (Fig. 80). However, that is dependent on a shading geometry, as the same size shading in a form of 5 louvers resulted in more glare and hence a higher frequency schedule (Fig. 81).

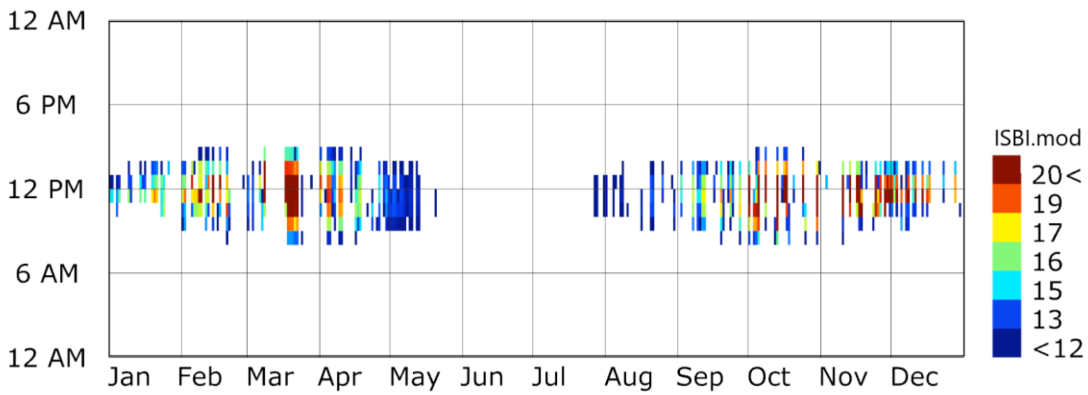

Figure 79. ISBI.mod for Stockholm climate – only values above 11.

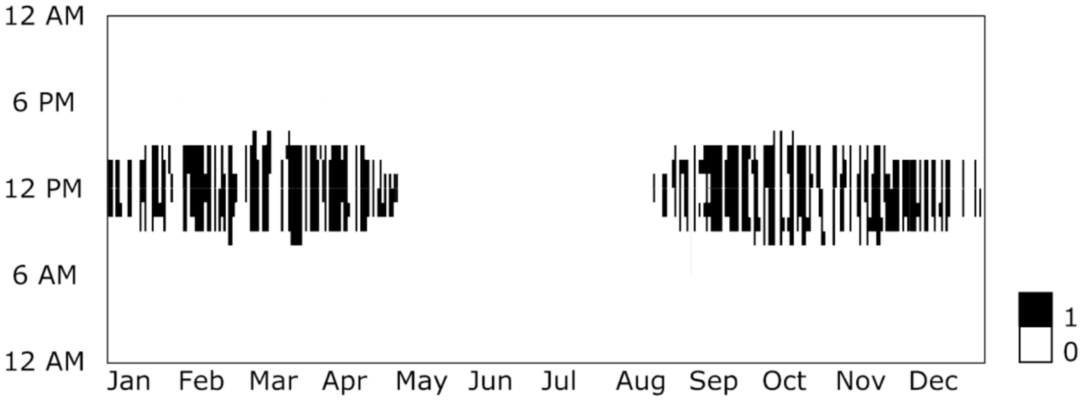

Figure 80. Internal blinds schedule (1 = ON, for DGP > 0.4) for Stockholm, clear glass WWR 44 %, OH100.

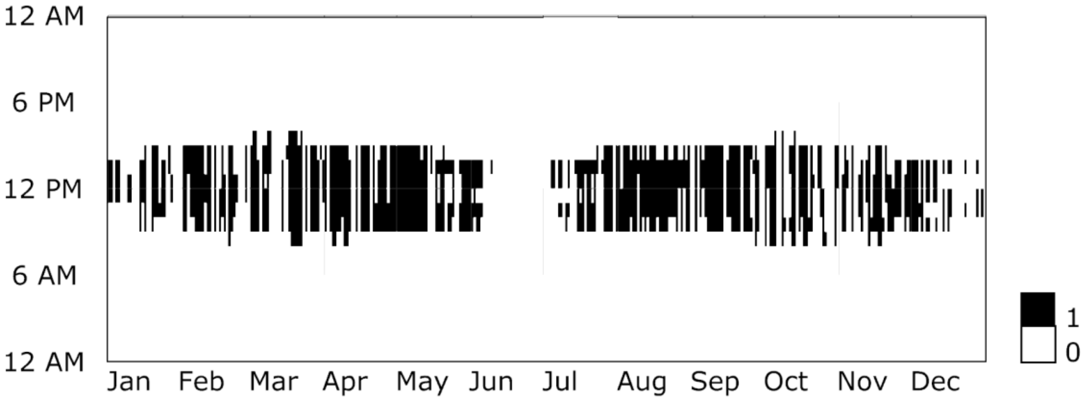

Figure 81. Internal blinds schedule (1 = ON, for DGP > 0.4) for Stockholm, clear glass WWR 44 %, 5HL20.

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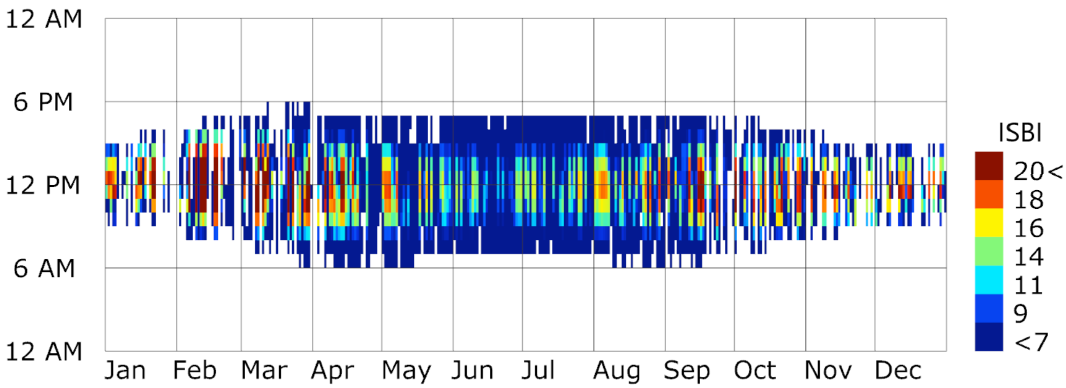

Figure 82. ISBI for Copenhagen climate.

Due to higher solar angles in Copenhagen, ISBI for high summer months is lower than for Stockholm (Fig. 82). Again, resemblance in the shapes of ISBI above 7 (Fig. 83) and the blinds schedule for a large window with clear glass (Fig. 84) can be observed.

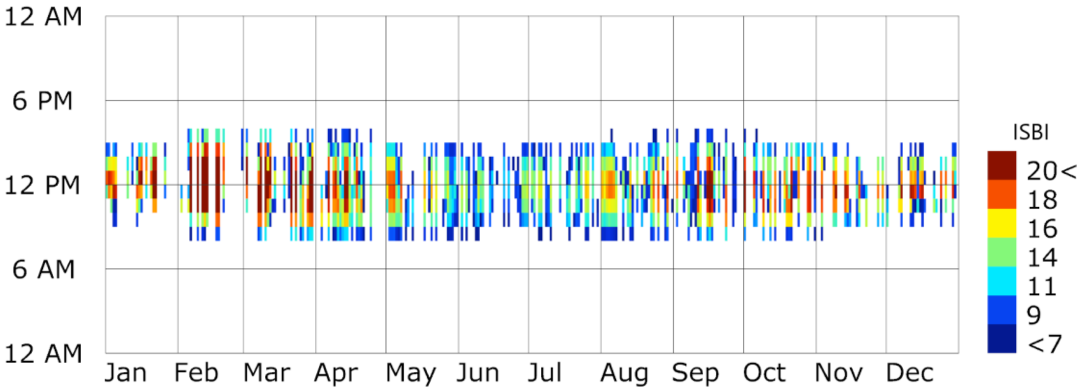

Figure 83. ISBI for Copenhagen climate – only values above 7.

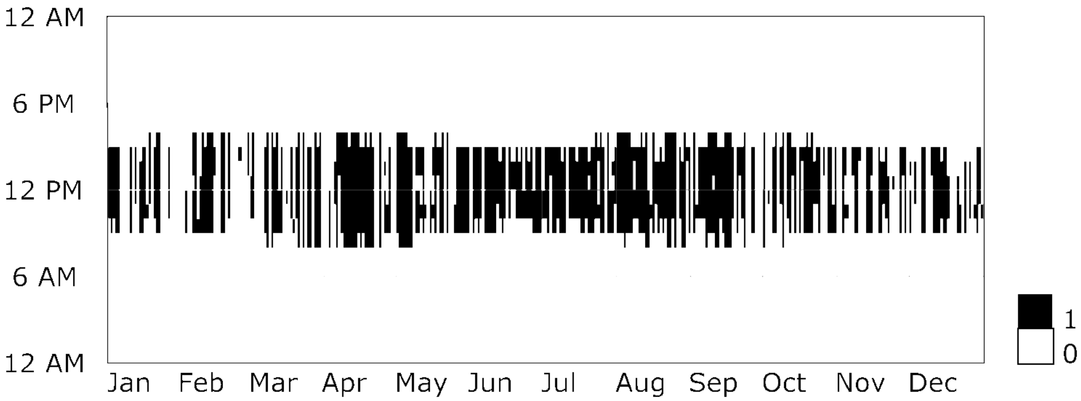

Figure 84. Internal blinds schedule (1 = ON, for DGP > 0.4) for Copenhagen, clear glass WWR 84 %, no external shading.

Figures 85 and 86 show charts of ISBI.mod with distinctly lower values for high summer, resulting in a shape that correlates better with the shape of selective glass window blinds schedule in Fig. 87.

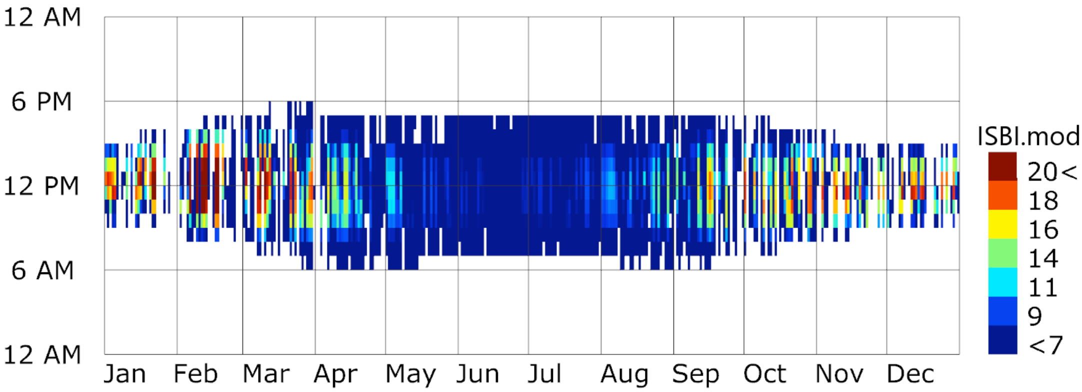

Figure 85. ISBI.mod for Copenhagen climate.

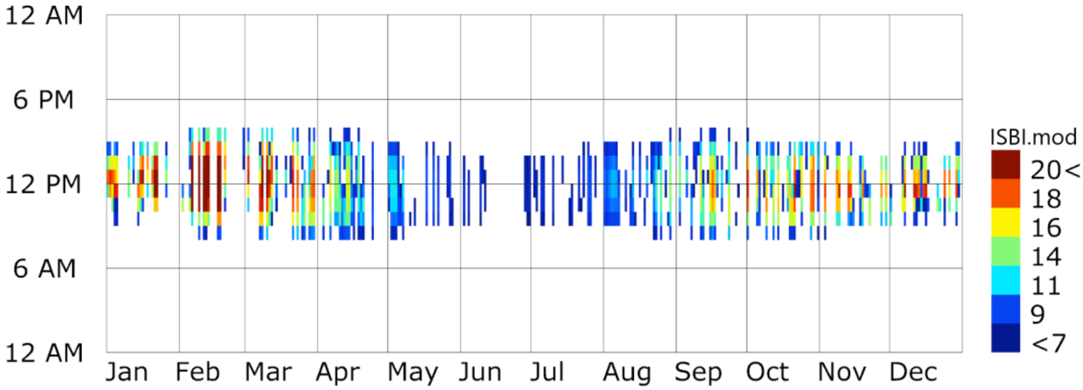

Figure 86. ISBI.mod for Copenhagen climate – only values above 7.

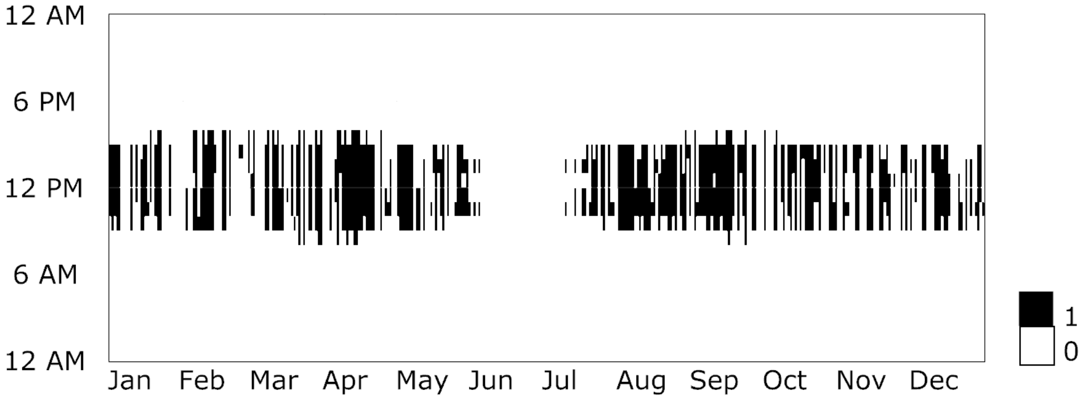

Figure 87. Internal blinds schedule (1 = ON, for DGP > 0.4) for Copenhagen, selective glass WWR 84 %, no external shading.

5. Discussion

5.1 Performance predictions and validation

5.1.1 Reference days

- Climate day types

First step of this method was categorisation of days from annual statistical weather data into relevant groups. Climate day types were established based on locally determined data set constraints. The proposed method of days categorisation can be used to compare various climates with one another by contrasting the local limit values (medians, quartiles) as well as by comparing the number of days in each category. Defining climate days for Swedish climates, it was noted that climate characteristics were easy to identify, however, it should be known that climates within Sweden are not too varied, therefore, further evaluation of climate day types could reveal if the method can apply to other weather scenarios. A limitation can be found in the way which determines low radiation day type '0', as this category will always include half of the yearly days because it is limited by the median of total daily solar radiation data. This may not apply to more sunny and hot climates, because the median can be high, which would mean that some days with high radiation are falsely regarded as low. Perhaps, a global total radiation limit should be sought. Otherwise, the climate day type method was found reliable as a way of selecting exemplary days that are representative to the whole year in a climate data file.

- Solar angles division

As a next step, solar angles for noon of each day were put into sets. The proposed solar angle limitations were found appropriate for northern low solar angle locations, such as Sweden, but for other climates the limits should perhaps be reevaluated.

- Predictions for annual performance

Looking at the simulation results for selected reference days A B C and D, predictions for the whole annual performance for Stockholm WWR 84 % can be made. By applying external shading device, cooling can be massively reduced while heating may increase only slightly. Increased lighting use was noted. Operative temperatures were, on the whole, lowered with external shadings. All of the above were validated and confirmed by annual results, however, there is no way of quantifying the annual performance based on RD predictions. It can be seen that on reference days B and C, which require cooling and also experience lower outdoor temperatures, a free cooling strategy may be considered. Glare occurs in all RD cases of unshaded window for 7 to 8 hours in a 10 hours work day, which means that regardless of solar angles, glare will persist. It is worth noting that glare simulations can be time-consuming and results depend on view position of an occupant. By simply only looking at a limited number of representative days in a year, glare cannot be fully understood. For instance, in case of 5HL40 shading, the results of glare were both positive, as glare was reduced for days B and C, but also negative as was observed on RD-D, when large HL type shading was less effective in glare mitigation than a smaller size OH type (Table 7). Thus, RD results might seem confusing as daylight and glare are in fact way more complex, therefore, it is deemed unsafe to make any predictions regarding annual performance when visual comfort is considered. Furthermore, since lighting is directly affected by the use of internal blinds, the annual use of electric lights is hard to predict. Not to mention that the lighting as a heat gain would have an impact on thermal balance, which suggests that predictions for an annual performance based on reference days are highly unstable.

As seen in section 4.1.5 ('Cooling conditions'), there are no transparent conditions in which it can be safely said that cooling will occur. Conditions of previous hours or even days will have a large impact on current thermal balance, since temperature of thermal mass, insolation, and diurnal temperature amplitudes are valid circumstances that have a decisive role.

The reference days method can be used to deepen the understanding of annual results and as a way of presenting to a contractor or a client in an easy-to-understand way what are the benefits and drawbacks of specific solutions. The method of selecting the RDs allowed to isolate sufficiently varied climate days. However, complex dynamic and interdependency of daylight and energy means that predictions of annual performance based on reference days could oversimplify the actual reality and wrong conclusions may be drawn. This is why reference days may not be suited as a prediction method for integrated daylight and energy studies.

It is suggested that perhaps it is not worth the extra time and effort to look at RDs for performance predictions. It takes a long time to isolate results of just the selected days from annual data sets and to then process the data. This might be a limitation of the simulation software that was used in this study, but since in this case simulations had to be run for the whole year anyway, it is better to look at the overall annual performance and only return to RDs for validation and better understanding in case of doubts.

5.1.2 Shading benefit index

- External

The proposed early prediction method of recognising the benefit that an external shading device may give, based solely on climate data found within a commonly used weather file format, is innovatory and was yet insufficiently tested. Nonetheless, thus far it has been shown that chart depictions of ESBI share a lot of similarities with annually simulated performance, as was seen in Figures 60 and 61 for Stockholm and Figures 64 and 65 for Copenhagen. At this stage of ESBI development, exact scales were not fully explored and translation of ESBI values within certain ranges was suggested but it should be further investigated. This means that the ESBI method does not provide exact quantities of solar heat reduction, as that will depend on building parameters and a chosen shading geometry. However, it was shown to have potential as a way of informing parties involved in a design process about the possible benefit of incorporating a shading device through a quick and easy chart visualisation of annual intensity and frequency of events when cooling can be substantially reduced by an external shading device in a given climate. As was previously mentioned (section 2.2), oftentimes shadings are overlooked by architects, therefore the aim of the ESBI is to emphasise the energy and comfort benefits without having to perform extensive simulations on an existing building design, and to include shadings in early design discussions before major architectural decisions have been made.

ESBI.vent as a modified version of ESBI was to serve as an early recognition of free cooling potential. The method may lack accuracy yet, but was shown reliable in recognising when in a year a benefit of an outdoor air cooling strategy can be observed, when compared with ESBI chart. Simulated cooling energy reductions made by addition of an external shading device were shown to be correlating to ESBI.vent critical periods (Fig. 62 & 63, Fig. 66 & 67). The actual link between DSR and outdoor temperature in ESBI.vent equation should be further studied, as the limit temperature for outdoor cooling was not determined but assumed. Free cooling strategy was carried out by a mechanical system, and it was not investigated whether the same applies to a naturally ventilated building.

- Internal

As was previously mentioned, glare simulations are time intensive. DGP is evaluated from an image that represents occupants field of view, and with many possible work stations, the number of simulations increase. There are many factors that would have an impact on the illuminances of the glare image as well as perception of the lighting scene, such as:

- Window height and width,
- Window transmittance,
- Room geometry and dimensions,
- Position of the occupant,
- Furniture,
- Internal light sources,
- Personal light sensitivity,
- Outdoor scene.

Currently, Daysim operated through Honeybee is not able to use more than one CPU (central processing unit) for glare image-based study, and thus glare simulations are slow. Time being an obstacle, many project managers might refrain from such tedious evaluations in favour of cutting costs. ISBI was developed in aim to overcome the above listed influencing factors and to save time. It has been shown that including operation of internal blinds into energy performance simulations will have an immense impact on the results (section 4.2, e.g. Fig. 36). ISBI was proposed as an early recognition tool to identify issues regarding visual discomfort based entirely on a weather file. It is has not been yet established what the scale of values translates to, thus next studies should determine the meaning of ISBI values and their correlation to glare. Perhaps in the future, using ISBI and linking it to window size and transmittance would facilitate accurate prediction of glare occurrence so that schedules for internal blinds operation could be based on ISBI results.

So far, it was shown that ISBI provides similar chart shapes to simulated combined DGP for occupants on each side of the room. It was also noted that ISBI works fairly well when compared to glare probability for a large clear glass window (Fig. 73 & 74, Fig. 83 & 84), but not as well for a smaller or selective glass window. Therefore, a modified version, ISBI.mod, was proposed as an alternative that accentuates low solar angles. Its chart shape was shown to approximately match internal blinds schedules for smaller window and selective glass (Fig. 78 & 75, Fig. 86 & 87). Rough estimation of glare inducing ISBI or ISBI.mod values pointed at 7 as a limiting value, however, those assumptions should be further verified. It was shown that higher ISBI values might relate to cases of partially mitigated glare e.g. where external shading was used (Fig. 79 & 80). There is a future potential in ISBI method, however, it is too early in the development process to produce a valid scale or deem the method successful.

5.2 Glazing type

Two types of glass were considered: clear and selective. It has been shown that selective glass can reduce the problem of glare and consequently provide more view to the outside in a year. However, it was also noted that selective glass compared to clear glass records higher use of electric lighting as less daylight is allowed in. In terms of percentage of occupancy time, the increase of electric lights use is usually higher than increase of view to the outside. Thus, there is a risk that interiors with selective glass windows may have a gloomy appearance.

It was noted that, on the whole, a smaller size external shading with selective glass recorded very similar performance to a large size external shading with clear glass in almost all studied cases. Except for few exemptions, small shading selective glass and big shading clear glass performed comparably in: EUI, cooling energy use, thermal comfort (by means of operative temperatures), and cooling peak load. The differences, on the other hand, were noted when looking at daylighting (or electric lights use) and view to the outside. In both metrics clear glass with large size external shading performed better in each studied climate or WWR (e.g. Fig. 43 & 44). Surprisingly, clear glass selection can ensure higher quality of visual environment while maintaining the same energy and thermal comfort results, provided it comes along with a larger external shading.

There is no reason for providing a large external shading device on a selective glass window, as improvements are rather negligible, and daylighting is compromised. Regarding Miljöbyggnad solar heat gain standards, selective glass satisfied the gold requirement, and it was shown that it might even be necessary in some cases when the gold criterion is sought for (e.g. Fig. 29), but silver and bronze standards can be attained as well with clear glass.

It was seen in the study that if, for some reason, an external shading device cannot be added onto a building south oriented facade, selective glass should unquestionably be a design choice. In relation to clear glass without external shading, it was shown to reduce energy, improve thermal comfort, provide better visual conditions, and minimise the size of a cooling system. Nonetheless, if the design and regulations allow, an external shading device should be added for improved performance results. Alternatively, other shading options can also be considered, although, those were not presented in this study. A compromise between lack of external shading and selective glass could be a fenestration design that incorporates venetian blinds type of shading inside a window (between panes), which usually necessitates an extra pane of glass for external weather protection of the shading device rather than thermal reasons. Furthermore, electrochromic glazing type as a shading strategy shows immense potential in reduction of glare and increase in natural daylighting, while effectively improving energy performance (Aldawoud, 2013).

5.3 External shading geometries

External shadings were tested in two Scandinavian climate conditions. It was shown that a fixed device placed on a southern façade of an office building saves annual EUI. Energy was largely saved mainly due to substantial reductions in cooling, while heating energy use was almost unaffected by shading devices. Slight increase was noted, however, the shading geometries still allowed for solar gains on heating winter days with low solar angles. However, considering visual comfort, many of the beneficial solar heat gain hours were shaded with blinds. Shadings were seen to decrease the operative temperatures, and noted more hours of occupancy with operative temperatures below the heating setpoint, however, it was checked that it never fell below 18 °C, as is required by Swedish BBR. Daylighting was reduced by external shadings, although, visual comfort was largely improved, as shadings minimised the occurrence of glare and ensured more time with an outdoor view in a year. Cooling peak load reduction means that a smaller cooling system can be designed, which can bring monetary as well as energy savings. Thermal comfort in summertime was also shown augmented. Seeing that most of the performance parameters, including energy and human comfort, benefitted from an external shading design, it was documented that fixed external shadings perform well in Scandinavian environments, which conventionally considered heating-dominated, nowadays are likely to experience excessive heat gains and increased cooling.

The main drawback of external shading devices was reduced daylight. In order to maintain other benefits, it has been suggested that efficient lighting strategies are considered in future projects:

- Daylight harvesting techniques with automated lights control,
- Dimming of the lights,
- Dividing the space lighting control into smaller sections based on their daylight availability,
- Ambient lighting setpoint reduced to 150 lux and use of individually operated task lights,
- Seeking special shading shapes and materials that increase the amount of diffuse daylight.

Future studies may involve analysis of automated movable external shadings, but high costs, high maintenance, and other socioeconomic factors (section 2.3) can be seen as weaknesses of such systems. Undoubtedly, there is a potential of higher energy savings with bespoke movable shadings, provided that maintenance is done on a regular basis. Most importantly, it should be agreed that external shadings should constitute an inseparable building component or integral part of a building design as their benefits are evident.

- Overhang vs. Brise-Soleil

Initial expectations that a brise-soleil type of shading would allow more daylight entering the room as the same size solid overhang were confirmed to an extent. BS shadings bring relatively small increase in daylighting, while can also slightly worsen glare issues. Regarding other performance metrics, the two external shading types performed almost identically. Advantages of BS over OH, as in smaller material consumption, and permeability to precipitation and heat, were mention in section 3.1.5. Whether an external overhang is solid or louvered can also force air passage through a building and facilitate a specific strategy for natural ventilation (section 2.4). The BS design can also be used to facilitate potentially more efficient solar energy harvest when integrating an active solar system on a shading device, due to preferable (or at least other than horizontal) sun oriented angles.

- Overhang/Brise-Soleil vs. Horizontal Louvers

An overhang type of external shadings (OH or BS) has proven more effective in glare mitigation than corresponding size horizontal louvers (as seen in from internal blinds schedules in Fig. 81 & 82) therefore provides better indoor comfort through longer presence of view out, and lower use of electric lights. Even though, theoretically OH/BS and HL should not be very distinct in their energy performance, due to different schedules for internal blinds and lighting, their respective results can be quite far, and HL tend to record worse performance. Additionally, since louvers partially obstruct the view, it can be seen as another disadvantage of the HL shading geometry.

- Angled Horizontal Louvers vs. Horizontal Louvers

Angled horizontal louvers were found to be the most effective type of studied external shading in glare mitigation, however, it was always at a cost of daylighting. Fixed AHL shading blocks a lot of daylight and the space would almost always need electric lights, which seems to be an unreasonable and undesirable choice. AHL shadings were efficient in other performance metrics like cooling reduction and thermal comfort, but the major benefit was that angled louvers help towards glare reduction, which was the main issue of non-angled horizontal louvers. There are, therefore, potential savings, but the AHL type of external shading device should be movable and automated in order to fully utilise its benefits.

- Vertical Fins

Vertical fins have shown to have small or no impact on the EUI, but helped reduce occurrence of glare. Effects of vertical shading elements should be further studied as there is a potential benefit. Importantly, it should be checked how much view is blocked by the fins for occupants looking out from a position at a higher angle, and whether this loss of view can be acceptable.

5.4 Internal shading

It is widely believed that windows of a larger size will bring in higher daylight utilisation. As was shown in this study, this impression might be far from true when visual comfort is accounted for. Highly glazed facades are responsible for increased glare issues, thus, would trigger more frequent employment of internal blinds. This was seen in Figures 43 and 44, in which base case without a shading device both with a smaller and a larger window resulted in identical electric lights use. This was a consequence of increased internal blinds use, as was shown that the annual share of occupancy with access to a view out can be as low as 60 % for a larger window. Comparison of lighting use with and without internal blinds (e.g. Fig 33) highlights the significance of visual comfort assessments and the necessity of working with internal lighting and blinds schedules. As was seen from cases without internal blinds, highest daylight utilisation was achieved by the base case without external shading. However, when taking into account visual comfort and operation of internal blinds, the above is no longer correct. It is clear that internal blinds operation affects the annual energy performance and significantly increases the EUI (e.g. Fig. 18), which suggests that visual comfort provisions should be included into building performance assessments. Generally, this study demonstrates how impactful the interdependence of daylight and energy is on performance metrics, to emphasise immense gravity of integrated simulations, and to encourage designers, engineers and architects to apply integrated daylight and energy approach in their practice.

5.5 Free cooling

Free cooling in this study was provided through a mechanical system operated with an air-side economiser. It was found to successfully mitigate overheating problems by flushing out warm indoor air and replacing it with cool outdoor air when its temperature was acceptably low. The exact behaviour of an air-side economiser was not analysed and the simulation results with free outdoor air cooling rely on default EnergyPlus algorithms. Nevertheless, it was observed that outdoor air temperature in Scandinavia is sufficiently cool to substantially reduce the cooling loads. Whether this strategy is simultaneously beneficial towards human indoor comfort is not known. Cold draughts are the main concern, and thus thermal comfort analysis should be carried out as a next step to validate the advantage of outdoor air cooling with increased airflow.

5.6 Side studies

- Daylight simulation quality sensitivity

It was seen (Table 6) that higher quality of daylight simulations can have a big impact on daylighting results, significantly ‘improving’ the performance. For this study it was good enough to use a lower quality, because it was only comparative. When trying to meet a specific standard or prove that a fenestration design ensures a well-daylit space, one should know that results of daylight simulations greatly improve with a higher simulation quality.

- Thermal zone modelling

Simulating the model as one thermal zone was a simplification made at a cost of daylighting. Two separate zones would record lower joint lighting use, which consequently would affect the results of heating and cooling, once more highlighting the impact of daylight on energy. Single zone modelling was sufficient for a comparative purpose of this study, but two-zone models are highly recommended.

- Reduced solar gain, increased lighting gain

It was observed that a reduction of solar heat gain may lead to increased use of electric lights, which add to the internal heat gain (Fig. 12). The bigger the shading, the more pronounced the problem gets. This effect should not be neglected, and perhaps daylighting improvement strategies mentioned above in section 5.3 could be introduced to help solve the issue of increased lighting. Future evaluation of advanced thermal comfort metrics could potentially help understand the advantages of larger shading from comfort rather than energy related perspective.

6. Conclusions

The thesis aimed to analyse solar shadings on a south facing fenestration in Sweden and it consisted of two distinctive parts – simulated case studies, and climate-based predictive methods.

The first part was intended to test various external shading geometries and glazing types in a framework of a south-oriented room model located in Copenhagen and Stockholm, by means of integrated daylight and energy simulation approach. Main findings of this study are listed below:

- Occupant interaction with internal blinds affects building performance results and should always be considered in annual simulations. Otherwise, wrong design conclusions can be drawn.
- Larger size of external shading with clear glass window has shown a similar annual performance to a smaller device with selective glass window. Comparing these fenestration design combinations, it was found that clear glass with large shading can provide higher visual comfort, while selective glass with small shading is more effective regarding thermal comfort.
- In case there is a lack of external shading device, selective glass is always preferable on a south-oriented fenestration.
- External shadings largely improve building performance in Swedish climate scenarios. It was found that external shading is better in terms of solar heat gain reduction, but can also improve visual comfort.
- Brise-soleil (louvered overhang) external shading geometry is superior to a solid overhang due to increased daylight, heat and precipitation permeability, less material used, and advantageous angles for solar energy systems.
- From a geometry perspective, corresponding size overhang and multiple louvers shade a window surface to the same degree, however, louvers tend to cause more glare, and thus, the overall building performance with horizontal louvers shading can be impaired. Thus, visual comfort assessments should always be considered.
- Angled horizontal louvers yield higher electric lights use as they block large amounts of daylight. Potential benefits of the design were shown, and those should be further explored, suggesting possibility of louvers adjustment in a movable and automated system.
- Vertical fins added to horizontal external shading elements can improve visual comfort and reduce energy use.
- Outdoor air cooling strategies were found suitable for Swedish climate due to low outdoor temperatures, and should be further evaluated as they can achieve substantial energy savings.
- Interdependence of light, glare, and internal heat gain reveals higher level of complexity in building operation, and the impact thereof should be accounted for in performance assessments through integrated daylight and energy simulations.

The second part of the thesis aimed to find alternative climate-based methods for quick and simple evaluation of internal and external shadings benefits. New early prediction methods were proposed, and are still in development stages and future validations using varied climate scenarios are necessary. Countless forms of the given equations are possible, and should be investigated. Thus far, it was found that:

- ESBI is a promising tool used for detecting of critical weather periods, in which an external shading device is expected to reduce overheating caused by solar radiation.
- ESBI.vent shows potential in recognition of free cooling opportunities when compared to ESBI, but the outdoor air cooling temperature limits should be further examined.
- ESBI.vent helps determine the most critical cooling periods in a climate year, when radiation and temperatures are high and an external shading device can substantially reduce cooling loads.
- ISBI and ISBI.mod show future potential as quick glare evaluation techniques, which may possibly lead to early internal blinds schedule estimation, however, it is in need of further development.
- Complex building performance simulations take a lot of time and manpower, therefore, climate-based evaluation techniques have been developed, and their potential as an early stage design tool is evident.

7. Summary

In recent years, the predominant focus of building energy-efficient strategies was the reduction of heating demand, achieved by limiting heat flow through a thermal envelope. Concurrently, as daylighting gained more recognition, large windows became very common in modern architecture. Highly glazed facades allow more sunlight into the space significantly increasing solar heat gain, and consequently causing overheating problems, even in northern latitudes, as heat gets trapped inside an air-tight and well-insulated building. Another disadvantage of high glazing ratios is the increased visual discomfort.

The first part of the thesis aims to analyse passive solar shadings on a south-oriented façade in Swedish climate scenarios, having predetermined that external and internal shadings' main function is solar heat gain and glare protection, respectively. Annual performance was assessed using an integrated daylight and energy approach. The study of several external shading geometries, two window sizes, and two glazing types was carried out using Radiance, Daysim, and EnergyPlus within Grasshopper for Rhino interface, and involved preparation of daylight-driven lighting schedules, and glare-driven internal blinds schedules, which were further applied to annual energy simulations. Comparative nature of the study allowed to evaluate and contrast thermal and visual performance of fixed external shading geometries, hinting that louvered overhangs may be preferable. However, acute interdependency between daylight availability and energy use, and their impact on indoor comfort metrics were found significant, which can ultimately hinder design optimisation. Nonetheless, it has been shown that solar protection in a form of a shading device or selective glazing type is vital to enhanced performance. Zone overheating was indeed present in the investigated cold climate scenarios, and the potential of external shadings and natural ventilation strategies on cooling reduction and comfort improvements was eminent. The chief study finding highlights the gross impact of internal shading operation on building performance and indoor comfort, thus schedules should be included in an annual simulation-based design process. Overall, the study articulated the applicability of integrated daylight and energy building analysis, as daylighting and occupants' interactions with building systems affect thermal performance estimations.

As the second part of the thesis, new climate-based prediction methods were developed. The proposed equations provide simple and quick visual representation of exclusively annual weather data with regard to shadings. External shading benefit index (ESBI) aimed to serve as an early design tool for recognition of high overheating periods, for which an external solar shading should be foreseen as it is expected to bring an immense benefit. Additionally, the tool can provide information about a cooling reduction potential with natural ventilation. Thus far, a fair correlation between the tool and a simulated result equivalent was found. Internal shading benefit index (ISBI) was developed as a tool for prediction of visual discomfort occurrences, during which an internal shading device would be required. The ultimate goal is to enable the use of ISBI as a prediction of glare in order to create preliminary blind schedules for annual energy simulations. This method demonstrates a great time-saving potential for a future design team, as it relieves the use of simulation tools, yet, it is too early to declare its usability. The new climate-based tools, albeit evident potential, need further development, meaning: evaluation of other possible equation forms, case study validation, and assignation of meaning to values in their relevant scales.

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