THE ENERGY BALANCE OF WINDOWS
- A study on residential spaces in the Nordic region

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1 Abstract

The continuous development of existing knowledge and efforts in the area of energy-efficiency in buildings brings attention to the energy balance of windows, meaning the comparison of heat losses versus heat gains, plus the additional electricity savings from lighting. This study focused on evaluating the energy balance of windows in building-code standard residential buildings in the Nordic region, in order to determine the effect of various parameters, such as window size, construction and orientation on the results and to identify guidelines for best design practice. Each window case was simulated in the context of a single room, using the dynamic energy simulation software “IDA ICE”. The results showed that in a Nordic climate, South-oriented windows with low U-values are capable of achieving a positive energy balance and that smaller windows with low U-values and moderate g-values are generally the optimum solution.
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2 List of Symbols and Abbreviations

° Degrees

× Multiplication symbol

ac/h Air changes per hour

AHU Air Handling Unit

C Celsius

g Solar energy transmittance through glazing

IGU Insulated Glass Unit

K Degree Kelvin

kWh Kilowatt-hour

lux Illuminance measurement unit

m meters

MET Ratio of work metabolic rate to resting metabolic rate

Pa Pascal, pressure unit

Tvis Visual transmittance through glazing

U Heat transfer coefficient, measured in W/m²K

Ug Heat transfer coefficient of the glazed area of a window

W Watt

WFR Window-to-floor area ratio

τe Direct component of solar energy transmittance

yr year
3 Introduction

Windows are accepted as a necessary element of any pleasant living space. They offer sunlight, fresh air and sometimes a view, which are all very important factors for the wellbeing of building occupants. Windows generally have a more complicated thermal function than insulated walls or roofs. In a new building construction, windows have a lower resistance to heat flow than the rest of the insulated building envelope. As a result, they are generally responsible for a higher share of the total heat losses. At the same time, their transparency allows solar heat gains and light into the building. Passive solar heat gains can positively contribute to the building’s heating load in the winter, while increasing its cooling load in the summer. However, the increase in cooling demand can be mitigated through natural ventilation and solar shading. The heating and cooling demands can vary significantly depending on glazing type and size, window orientation and whether shading is implemented or not. Besides the effect on the heating and cooling loads, windows can reduce the electric lighting demand by providing natural light. Considering all these parameters, effective window design is a complicated process that requires thorough investigation of the impact on heating, cooling and lighting. This study aims at shedding light on these issues.

3.1 Objectives

The main objective of this study is to investigate the influence of various window-related parameters, such as glazing type and size, orientation, inclination and shading, on the energy balance of residential spaces located in cold climates. The energy balance in this study refers to the energy demand for space heating, cooling of the supply air and electricity for lighting. A secondary objective is to determine the effect of each parameter on thermal comfort and daylight availability in the studied spaces. The conclusions from this study provide information and guidelines that contribute to the design of low energy and highly comfortable residential spaces in Nordic climates.

3.2 Scope

This study focuses on the energy performance of residential spaces in a Nordic climate. Each window case is simulated in the context of a single room, which is assumed to function as a “living room”. Three room geometries are studied, but in all cases the construction complies with the Swedish building code for new residential buildings. Therefore, the conclusions from this study do not necessarily apply to non-residential buildings, buildings with other construction types, or buildings located in different climatic regions.

Parameters that were investigated include window size and inclination, orientation, glazing construction and shading. The climate, building construction, ventilation rate and internal loads are assumed constant throughout the study.

Based on the window inclination, three different room geometries are simulated in this study. Due to differences in the external surface area in each of the models, their absolute results are not comparable. Therefore, this study does not evaluate the performance of different window
inclinations, but rather identifies optimal solutions in each case and concludes on general trends.  

This study aims at investigating the impact of windows on the energy balance, thermal comfort and daylight availability of the defined cases. More specifically, the results are limited to the following parameters:

- Annual heating demand and peak load
- Annual cooling demand and peak load
- Annual electricity demand for lighting
- Total annual energy demand (heating, cooling and lighting)
- Annual overheating hours, with a threshold of 25°C
- Average and maximum daylight illuminance

Other performance indicators, such as indoor air or lighting quality, were not investigated in this study.

Finally, this study is entirely based on simulations, so all results require further validation through full-scale measurements.

### 3.3 Background

Several previous studies have addressed the topic “energy balance of windows”. Persson (2006) studied the effect of different window configurations on the heating and cooling demand of residential and office buildings in various climates, through a series of energy simulations with the dynamic energy simulation program “DEROB-LTH”. She evaluated four different window types in residential buildings, with U values ranging between 0.54-2.9 W/m²K, and varied the glazing-to wall ratio from 0% to 84%. She showed that the windows with low-e coating (cases with U=1.3 W/m²K or lower) perform almost the same, in terms of annual energy use, regardless of window size. Her study also indicated that a more thermally resistant building allowed for more flexibility in the window properties, including size, construction and orientation (Persson, 2006). With this study as a foundation, the effects of windows on low-energy houses in Sweden were further investigated by Persson, Roos & Wall (2006). These authors pursued the goal to analyze whether the common practice of placing large windows on the South and smaller windows on the North side was indeed the optimal solution for low-energy residential buildings in cold climates. This study was also carried out through energy simulations using the program “DEROB-LTH”. A low-energy house with a total window-to-floor area of 16% was used as a reference case, and from there the window area on the South was varied. Contrary to the initial hypothesis, their research indicated that the reverse configuration - smaller windows on the South (20% or even 50% less than the initial building) and larger ones on the North (enough to provide a total window-to-floor area of 10%) - actually resulted in a much lower annual energy demand. This was mostly due to a significant reduction (13% or more) in the cooling energy required, while the heating demand was also lower, albeit negligibly. However, if a passive cooling strategy like shading or natural ventilation had been applied in this study, perhaps the total energy demand would be
almost unaffected. This, in combination with the fact that larger windows on the South result in more daylight, means that the original placement might be in fact optimal in reality. Another interesting result from this study was that a low-energy house without windows would require much less energy for heating and cooling than the same house with any combination of windows (Persson, et al., 2006). Of course, a house without windows would not be preferred for other reasons, so this is a completely hypothetical situation.

In Italy, Gasparella et al (2011) investigated the impact of windows on the energy balance of low-energy residential buildings, but in more moderate European climates (Milan, Nice, Paris and Rome). They used the dynamic energy simulation program “TRN-SYS” to predict the energy performance of the building with different window configurations. The investigated windows had a thermal conductance ranging between 0.6-1.4 W/m²K and a g-value ranging between 0.4-0.61, while the window to floor area was varied from 16% to 41%. They found that while the window U and g values played the most important role during the heating season, it was the window size that mainly determined the cooling demand. This study also indicated that in these climates, the additional solar gains from a larger window overcompensate for the night-time heat losses, resulting in a lower heating demand (Gasparella, et al., 2011). This is contrary to the results found by Persson et al (2006) for Sweden, which is understandable since there is much less solar heat available during the heating season in Sweden. Very recently, Tsikaloudaki et al (2015) looked into the energy performance of different window constructions (U=0.72-3.2 W/m²K, g=0.3-0.72) in Mediterranean climates. Their study, which was based on the ISO 18292 guidelines for calculating the heating and cooling energy indices, indicated that window construction has the most significant effect on the energy balance, compared to other factors such as window size and orientation. The optimum solutions for these warm climates proved to be windows with high thermal conductance (U=2.6 W/m²K) and low solar transmittance (g=0.3). Windows with lower U-values did not perform as well in this region, as they reduced the heat transfer from the building to the outside during the warm season, thus increasing the already significant cooling demand (Tsikaloudaki, et al., 2015).

Another recent study in a heating-dominated region (Kull, Mauring & Tkaczyk, 2015) examined the effect of the g/U₉-value ratio on the energy balance of windows. This study was based on heating energy calculations according to ISO 13790. The different glazing types examined had U₉ values between 0.4-1.1 W/m²K and g values ranging from 0.42 to 0.62. Their results showed that windows with a higher g/U₉ ratio (0.9-1.18) have an optimal performance in the Nordic region. Additionally, they found that North-oriented glazing always had a negative energy balance, meaning that the solar gains did not compensate for the heat losses, while the reverse was usually true for South-oriented windows. This of course, only refers to the heating season. If the cooling demand had also been taken into consideration, perhaps the results would be in line with those from Persson et al (2006) i.e. that windows on the North side yield an overall lower annual energy demand (for heating and cooling). One key result from this study was that on all orientations except the South, the U₉ value was the main parameter determining a window’s energy performance, whereas on the South, the dominant factor was the g value (Kull, et al., 2015).
Grynning et al (2013) carried out a study in the context of office buildings in Norway with the aim to determine whether windows in future buildings will be net energy “losers or gainers”. Different window constructions (U=0.2-1.0 W/m²K, g=0.2-0.8) in a low-energy office building were studied using the dynamic energy simulation program “EnergyPlus”. This research team showed that windows could be either energy losers or gainers depending on their construction, and concluded that windows with very low U- and g-values (U=0.4 W/m²K, SHGC=0.4) could in fact outperform a highly insulated wall (U=0.15 W/m²K) (Grynning et al., 2013).

Some studies have investigated both vertical and sloped windows, and have reported that they perform quite differently, mostly because sloped windows are more exposed to the sky, which affects both their access to sunlight and their heat losses. Gillmor, Theriot & Reilly (2011) studied the annual energy performance of different window configurations in residential buildings in various locations across North America. They used the dynamic energy simulation program “DOE-2” to examine the impact of different glazing sizes and distributions among the facades. All window cases were designed to achieve an average daylight factor of 5%. The results show that skylights can provide the same daylight conditions as façade windows with less glazing surface, therefore maintaining lower heating and cooling demands, despite the fact that sloped windows generally have a higher U-value. Their study also showed that South-facing skylights perform better in colder climates, while North-facing skylights should be preferred in warmer climates (Gillmor, et al., 2011). A study based on the net energy gain method described in ISO 13790, which was performed by Kragh, Birck Laustsen and Svensen (2008) in various European climates, also confirmed that sloped windows outperform vertical ones in terms of their balance on heating, cooling demands and illumination. Additionally, they found that the ranking of windows, according to their thermal and optical properties (U- and g-values), from best to worst performance, was the same for both sloped and vertical windows and did not vary by location (Kragh, et al., 2008). In Belgium, the Belgian Building Research Institute (2011) investigated the energy balance of various windows in old and renovated houses by energy calculations based on ISO 13790 and ISO 18292 and also found that sloped windows performed better in terms of energy use and illumination than vertical ones. This study also concluded that the window ranking was unaffected by the slope of the windows or even by the building construction, comparing between buildings before and after renovation. However, what qualified as “optimal” windows were not the ones with low g values (0.3), as might have been expected, because the loss of passive solar heat gains during the winter outweighed the savings obtained during the cooling season (Belgian Building Research Institute, 2011). A study carried out by Panek, Rucińska and Trząski (2010) on residential buildings in Poland, which also followed the calculation methods described in ISO 13790 and ISO 18292 for the energy balance of windows, yielded similar results regarding the ranking of glazing types and the difference between sloped and vertical windows. This study also indicated that windows with very low thermal conductance (U=0.8-1 W/m²K) did not actually perform the best during the heating season, most likely because of reduced solar gains, a property which usually accompanies low U-value glazing (Panek, et al., 2010).

All the studies mentioned so far have focused solely on the effect of windows on heating and cooling energy. In a study carried out by Foldbjerg, Roy, Duer & Andersen (2010), the
potential for lighting energy savings was investigated as well, in the context of a residential building in four climates (Berlin, Paris, Rome and Istanbul), through energy simulations using “EIC Visualizer”, which is an interface for the dynamic energy simulation program “IDA ICE”. The reference building case was the only one with a window. Three more cases were simulated: one where the electric light was set to provide illumination levels equal to those of daylight, one where it was set to provide a maximum illumination of 500 lux, and a final case where the electric lighting was set to provide up to 200 lux. The results from this study generally indicated that windows always reduce the total energy demand, in terms of heating, cooling and electricity for lighting (Foldbjerg, et al., 2010). More recently, a research team from Sweden (Du, Hellström & Dubois, 2014) also analyzed the effect of windows on heating, cooling and lighting in Swedish and French detached houses using the dynamic energy simulation program “DesignBuilder”, which is an interface to “EnergyPlus”. In the French house, the energy use was always lower when the building had windows, which confirms the findings of Foldbjerg et al (2010), but in the Swedish house, the case without windows had one of the lowest total annual energy demands, which is in line with the results obtained by Persson et al (2006). This is most likely due to the Swedish climate, where there are limited solar heat gains during winter and increased solar gains during summer, thus increasing both the heating and cooling demands compared to a building without windows. One additional conclusion was that the whole building construction (U-value of walls, roof, floor) plays an important role in the overall energy balance. Depending on the window case, the electricity demand for lighting was reduced by 23% to 42% by the use of daylight. The electricity demand was less affected by window size compared to the heating and cooling demands since sufficient daylight levels (150 lux) were obtained with fairly small windows. Finally, it was concluded that in warmer climates, solar gains through a window can compensate for nighttime heat losses, as was the case in the French house (Du, et al., 2014), which is in line with the findings of Gasparella et al (2011).

In conclusion, previous work on this topic can be summarized as follows:

- **In cold climates:**
  a) Window U- and g-values determine the energy balance. Low U-values and high g-values are optimal for the heating season. The g-value has a greater impact on South-oriented windows.
  b) The passive solar heat gains through a South-oriented window can compensate for nighttime heat losses, while most likely not on a North-oriented window.
  c) South-facing skylights yield the best performance in terms of heating and cooling demand.
  d) The performance ranking of glazing constructions (U- and g-values) remains the same for vertical and sloped windows.
  e) A building with no windows results in less annual energy use than a building with windows.

- **In moderate climates:**
  a) The U- and g-values are the most dominant factors for energy performance during the heating season, while window size is more important during the cooling season.
  b) Larger window size results in a reduction in the heating demand, due to increased solar heat gains.
c) Skylights can result in the same illumination with less window area, therefore reducing the heating and cooling demands.
d) The performance ranking of glazing constructions (U- and g-values) remains the same for vertical and sloped windows, and for windows in older and newer building constructions.
e) A building with no windows yields higher annual energy use than a building with windows.
• In warm climates:
  a) The U- and g-values are the most dominant factors affecting the annual energy performance. High U-values and low-g-values are the optimal solution.
  b) North-facing skylights perform the best in terms of heating and cooling.

3.4 Research hypotheses

Based on the literature review, the following research hypotheses were formulated:

1. Glazing construction (U- and g-values) will have a higher impact on the energy balance than orientation. A more thermally resistant window (i.e. low U-value) will outperform a less resistant one on all orientations.
2. Window orientation will have a greater effect on all parameters when the window is located on the façade rather than the roof.
3. The heating demand will be higher as the window size increases.
4. The highest indoor temperatures will occur on the West-oriented cases, where the solar heat gains will coincide with the occupied hours of the building.
5. Low window g-values will have the strongest impact on reducing overheating hours when the window is oriented towards the South or West.
6. The implementation of insulated exterior shading will significantly reduce overheating hours and will slightly reduce the heating demand.
4 Method

4.1 Overview

This study was carried out in three main stages: research and project definition, energy and indoor climate simulations and finally, result interpretation. First, several relevant research projects were reviewed in order to get an overview of the existing knowledge in the field and to compare conclusions. Following this, a set of research goals was defined and decisions were made as to the appropriate study cases and variable parameters. A list of expected results was drafted before any simulations were performed.

After the building cases had been carefully defined, they were simulated in the software “IDA ICE” in order to find the energy performance and indoor climate conditions in each case. These results were organized and reviewed in an Excel spreadsheet in order to find patterns and draw conclusions. The conclusions were subsequently compared to those from previous studies and to the initial hypotheses.

4.2 Tools

Following is an overview of the software used during this project:

- *IDA Indoor Climate and Energy* was the dynamic energy simulation program used to calculate the energy performance and indoor climate conditions of the defined room cases.
- *Microsoft Excel* was utilized to create an overview of the results and generate graphs, which was the main method for evaluating the results.
- *Trimble SketchUp* was the 3D modelling program used to visualise the simulated room geometries.

4.3 Simulation cases

4.3.1 Constant parameters

4.3.1.1 Location

For the purposes of this study, it was considered useful to simulate the energy balance in a location that would be representative of the Scandinavian climate and of a significant percentage of the regional population. Stockholm, Copenhagen, Oslo and Helsinki were therefore compared in sample simulations, in order to determine which location presented conditions closest to the average. The simulation results used in this decision were the heating energy, cooling energy and electricity for lighting, see Figure 1. Stockholm and Oslo presented very similar results and were near the average. In the end, Stockholm was selected, as it has been used in similar studies, thus enabling a more accurate comparison of results.
4.3.1.2 Construction

The building models in this project are assumed to be new constructions that follow the Swedish Building Code. Therefore, the external walls are designed to have a U-value of 0.18 W/m²K and the roofs 0.13 W/m²K. Neither the walls nor the roofs include any thermal mass, such as concrete or bricks.

The infiltration rate was set to 0.61 l/s per m² of external surface, which is the maximum rate set by the Swedish standard. This corresponds to an air change rate of 1.3 ac/h at 50 Pa for the models with façade windows, 1 ac/h for the models with 45° roof windows and 1.2 ac/h for the models with 15° roof windows. For more information on the building models, see section 4.3.2.1.

In all building cases, the window frame U-value is assumed 2 W/m²K and amounts to 2% of the total window area.

4.3.1.3 Indoor air quality

The indoor air quality in the building models is regulated by a constant airflow ventilation system. The supply air temperature was set to 16°C and the ventilation rate to 28 l/s, which corresponds to 7 l/s for each of the room occupants. According to the European standard EN 15251-2007, the minimum required ventilation rate in residential buildings is either 7 l/s per occupant or 1 l/s per m² of floor area, whichever is higher (CEN, 2007). The AHU has both a heating and a cooling coil, so the incoming air is either heated or cooled to 16°C. There is also a heat exchanger in the AHU, with an efficiency rate of 75%, and it is designed without
a bypass, which means that the extract air from the room always exchanges heat with the incoming fresh air.

Concerning the total heating demand, this is the sum of the energy required by the heating coil in the AHU, in order to heat the supply air to 16°C, and of the room heating unit, which is set to turn on when the operative temperature is 20°C or lower. Regarding the cooling demand, this is the energy required by the cooling coil in the AHU in order to maintain a constant supply air temperature of 16°C. There is no additional cooling unit in the room. This means that overheating can still occur.

4.3.1.4 Light levels

The electric lighting is adjusted according to the available daylight. When the average level of natural light on a horizontal surface is below 100 lux, then all electric lighting is on. From 100 to 300 lux of available daylight, the electric lighting is switched on proportionally, so that the indoor illuminance is constantly 300 lux. When the natural light levels are equal to or above 300 lux, then all electric lights are turned off. The threshold of 300 lux was selected based on the IESNA guideline for casual reading tasks (Illuminating Engineering Society of North America, 2000).

4.3.1.5 Internal loads

The internal heat loads are the same in all building cases and are summarized in Table 1.

<table>
<thead>
<tr>
<th>Internal load</th>
<th>Intensity</th>
<th>Unit</th>
<th>Schedule</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occupants (4)</td>
<td>1.2 each</td>
<td>MET</td>
<td>Mon-Fri 6-8, 15-22, Sat-Sun 8-10, 13-22</td>
</tr>
<tr>
<td>Lights</td>
<td>4.2</td>
<td>W/m²</td>
<td>(same as occupants)</td>
</tr>
<tr>
<td>Electronic devices:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laptops (2)</td>
<td>45 each</td>
<td>W</td>
<td>Mon-Fri 18-20</td>
</tr>
<tr>
<td>Television</td>
<td>50</td>
<td>W</td>
<td>Everyday 20-22</td>
</tr>
</tbody>
</table>

4.3.1.6 Window opening control

In all simulation cases, the windows open for natural ventilation when the operative temperature is above a certain threshold, the outdoor temperature is lower and the building is occupied, see section 4.3.1.5. Between 23°C and 24°C, the window opening is proportional to the indoor temperature. At 24°C or higher the window is fully open.
4.3.2 Variable parameters

Table 2 shows an overview of the variable parameters in this study and their assigned values. The simulation cases were defined by crossing all of these parameter values, resulting in a total of 204 cases.

Table 2. List of variable parameters and their respective values.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Window angle</td>
<td>90°</td>
</tr>
<tr>
<td></td>
<td>45°</td>
</tr>
<tr>
<td></td>
<td>15°</td>
</tr>
<tr>
<td>Orientation</td>
<td>South</td>
</tr>
<tr>
<td></td>
<td>North</td>
</tr>
<tr>
<td></td>
<td>East</td>
</tr>
<tr>
<td></td>
<td>West</td>
</tr>
<tr>
<td>Glazing-to-floor ratio</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>30%</td>
</tr>
<tr>
<td>Glazing construction</td>
<td>$U_g = 1.1 \text{ W/m}^2\text{K}$, $g = 0.64$, $T_{vis}=0.81$</td>
</tr>
<tr>
<td></td>
<td>$U_g = 1.0 \text{ W/m}^2\text{K}$, $g = 0.51$, $T_{vis}=0.75$</td>
</tr>
<tr>
<td></td>
<td>$U_g = 1.0 \text{ W/m}^2\text{K}$, $g = 0.30$, $T_{vis}=0.61$</td>
</tr>
<tr>
<td></td>
<td>$U_g = 0.5 \text{ W/m}^2\text{K}$, $g = 0.50$, $T_{vis}=0.65$</td>
</tr>
<tr>
<td>Shading</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>No</td>
</tr>
</tbody>
</table>

4.3.2.1 Model Geometry

Three different building geometries were simulated in this study: a 90°-window geometry, a 45°-window geometry and a 15°-window geometry. On each of these, the window-to-floor ratio (WFR) was either 0%, 10% or 30%, resulting in nine total building geometries, see Figure 2. The grey surfaces represent the roof (dark grey) and external wall (light grey). All other surfaces are considered internal and adiabatic.
The energy balance of windows
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Method

Figure 2: The nine building geometries that were simulated in this study.

The floor area in all room geometries is 5m×4m (20m²) and the window sizes are either 1.25m×1.6m (2m²) or 3.75m×1.6m (6m²), which correspond to 10% and 30% of the floor area respectively.

In the 90° and 45° window geometries, the window is placed 0.9m above the floor, following common practice. In the 15° window geometry, the window is centered on the roof surface.

4.3.2.2 Orientation

All building cases, including the windowless versions, were simulated on four orientations: South, North, East and West.

4.3.2.3 Glazing size

Besides the cases without windows, this study examines two different window sizes:

- 1.25m×1.6m, which corresponds to 10% of the floor area in all building geometries
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- 3.75m×1.6m, which corresponds to 30% of the floor area in all building geometries

4.3.2.4 Glazing construction

Four different glazing types were selected for the purposes this study, and are based on characteristics of existing VELUX insulated glass units (IGU). All glazing types are capable of fulfilling the Swedish building code requirement for window U-values, according to which they should be no higher than 1.3 W/m²K. After this initial condition, the glazing types were selected based on their $U_g$, g-value and visual transmittance ($T_{vis}$), with the goal to have some similarities among the selected cases, which would enable a more accurate interpretation of the simulation results. Table 3 presents all the characteristics of the selected glazing types.

Table 3. Characteristics of the glazing types simulated in this study.

<table>
<thead>
<tr>
<th>Glazing type</th>
<th>$U_g$ [U/m²K]</th>
<th>g</th>
<th>$T_{vis}$</th>
<th>Related VELUX product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glazing type A</td>
<td>1.1</td>
<td>0.64</td>
<td>0.81</td>
<td>IGU 50</td>
</tr>
<tr>
<td>Glazing type B</td>
<td>1.0</td>
<td>0.51</td>
<td>0.75</td>
<td>IGU 59</td>
</tr>
<tr>
<td>Glazing type C</td>
<td>1.0</td>
<td>0.30</td>
<td>0.61</td>
<td>IGU 60</td>
</tr>
<tr>
<td>Glazing type D</td>
<td>0.5</td>
<td>0.50</td>
<td>0.65</td>
<td>IGU 62</td>
</tr>
</tbody>
</table>

4.3.2.5 Shading

All building cases with windows were simulated with and without shading. The shading device was an external dark translucent screen with the characteristics described in Table 4. It is based on the black VELUX Awning Blind.

Table 4. Shading device properties.

<table>
<thead>
<tr>
<th>Glazing type</th>
<th>$U_g$ [U/m²K] with shading</th>
<th>g with shading</th>
<th>$T_{vis}$ with shading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glazing type A</td>
<td>1.05</td>
<td>0.18</td>
<td>0.14</td>
</tr>
<tr>
<td>Glazing type B</td>
<td>0.96</td>
<td>0.16</td>
<td>0.14</td>
</tr>
<tr>
<td>Glazing type C</td>
<td>0.96</td>
<td>0.13</td>
<td>0.10</td>
</tr>
<tr>
<td>Glazing type D</td>
<td>0.48</td>
<td>0.12</td>
<td>0.11</td>
</tr>
</tbody>
</table>
In the simulation cases with shading, it is activated when the operative temperature exceeds 24°C and when the solar angle is equal to or lower than 0° (at night-time).
5 Results

The results from the dynamic energy and indoor climate simulations are displayed in this chapter, separately for each model geometry (refer to section 4.3.2.1) and organised by output type. All results refer to annual values. Any graphs displaying results that were considered redundant are not displayed in this chapter. Refer to the appendix for an overview of all simulation results.

Four windowless building cases were studied for each building geometry, where the one external wall was facing the South, North, East and West respectively. The building cases with windows are always compared to the windowless version facing the same direction.

5.1 90°-window geometry

5.1.1 Heating demand

Figures 3–6 show that some South-oriented window cases managed to achieve a slightly lower heating demand than the equivalent building case without a window. For all glazing types and sizes, a South orientation results in the lowest heating demand, followed by the West, then the East and finally the North. The use of shading proved to cause a negligible reduction of the heating demand in all cases, therefore the results are not displayed in this chapter, but can be found in the appendix.

![Graph](image)

**Figure 3.** Annual heating energy demand for building cases with glazing type A: $U=1.10 \text{ W/m}^2\text{K}$, $g=0.64$, $T_{vis}=0.81$.

**Figure 4.** Annual heating energy demand for building cases with glazing type B: $U=1.00 \text{ W/m}^2\text{K}$, $g=0.51$, $T_{vis}=0.75$. 


5.1.1.1 Glazing type A: U=1.10 W/m²K, g=0.64, T\textsubscript{vis}=0.81

From Figure 3 it is apparent that the 10% WFR case on the South has a 10% (3.9 kWh/m²yr) lower heating demand than the windowless case. No other window case with this glazing type has a lower heating demand than the windowless case. The 30% WFR case on the South increases the heating demand by 7% (2.8 kWh/m²yr) compared to the 0% window case. The North-oriented windows result in the highest heating demand. A 10% WFR on the North results in a 14% (5.5 kWh/m²yr) increase in the heating demand compared to the same building case without a window. A 30% WFR on the North results in a 49% (19.8 kWh/m²yr) increase compared to the windowless case. A large window (30% WFR) on the South results in a lower heating demand than a small window (10% WFR) on the North or East.

5.1.1.2 Glazing type B: U=1.00 W/m²K, g=0.51, T\textsubscript{vis}=0.75

It is evident from Figure 4 that the resulting heating demands from this glazing type follow the same trends as glazing type A, with all values only slightly higher. A 10% WFR on the South reduces the heating demand by 6% (2.4 kWh/m²yr) compared to windowless case. All other window cases increase the heating demand compared to the windowless case. A 30% WFR on the South increases the heating demand by 11% (4.3 kWh/m²yr) compared to the equivalent windowless case. A 10% WFR on the North increases the heating demand by 15% (6 kWh/m²yr), while a 30% WFR on the North results in a 50% (20.1 kWh/m²yr) increase compared to the North-oriented windowless case. Again, the 30% WFR case on the South results in a lower heating demand than the 10% WFR case on the North and East.
5.1.1.3 Glazing type C: U=1.00 W/m²K, g=0.30, T
vis=0.61

As shown in Figure 5, this glazing type results in the highest heating demand compared to all other glass constructions. No window cases have a lower demand than the windowless cases and increasing the WFR from 10% to 30% leads to a very significant increase in the heating demand. All 30% WFR cases have a higher heating demand than the cases with a 10% WFR. Compared to the equivalent windowless case, the South-oriented 10% WFR case increases the heating demand by 6% (2.2 kWh/m²yr), while the case with 30% glazing on the South results in a 30% (11.5 kWh/m²yr) increase. As for North-oriented windows, 10% glazing results in a 20% (8.2 kWh/m²yr) increase of the heating demand while 30% glazing results in a 40% (25.3 kWh/m²yr) increase compared to the windowless case.

5.1.1.4 Glazing type D: U=0.50 W/m²K, g=0.50, T
vis=0.65

Figure 6 clearly shows that this glazing type results in the lowest overall heating demand and that glazing size has a milder impact on the results, compared to the other glazing types. Both tested window sizes, 10% and 30% WFR, when facing the South, result in a lower heating demand compared to the case without windows. The heating demand of the 10% WFR case is 14% (5.4 kWh/m²yr) lower and that of the 30% WFR is 10% (3.8 kWh/m²yr) lower. A 30% WFR with this glazing type has the same impact on the heating demand as a 10% WFR with glazing type A. In addition, a 30% WFR on the South with this glazing type has the same impact on the heating demand as the 10% WFR with glazing type A, and a lower demand than a 10% WFR with glazing types B and C.

5.1.2 Heating power

The peak heating power does not seem to be significantly affected by glazing type, orientation or the use of shading. Figure 7 shows the results obtained with glazing type B without shading, which are similar to those obtained with the other glazing types, both with and without shading. There are only two exceptions to this: First, the case with a 30% WFR with glazing type A on the South, where the use of shading reduces the peak load by 5% (2.5 W/m²) compared to the same case without shading, and secondly a noticeable reduction in the heating peaks of cases with glazing type D, especially for larger window areas. The case with 30% glazing type D on the South has a 7% (3.7 W/m²) lower peak than the same case with glazing type B.
5.1.3 Cooling demand

These results refer to the cooling demand of the mechanical ventilation system, as the studied room cases do not have space cooling. The cooling demand does not vary much between the different glazing types and is not significantly affected by the use of shading. Most cases have the same results as glazing type B without shading, shown in Figure 8.

Figure 7. Maximum heating power required by building cases with glazing type B: $U=1.00 \text{ W/m}^2\text{K}$, $g=0.51$, $T_{\text{vis}}=0.75$, without shading.

Figure 8. Annual cooling energy demand for building cases with glazing type B: $U=1.00 \text{ W/m}^2\text{K}$, $g=0.51$, $T_{\text{vis}}=0.75$, without shading.
It is evident that glazing size also does not affect the results significantly. The cases with 0% WFR have the lowest demand, then increase as the WFR increases to 10%, but increasing the window area further does not result in a significant increase in the cooling demand. As for the different orientations, the South, East and West perform similarly, while the North-oriented cases have a slightly lower cooling demand.

5.1.4 Cooling power

Similarly to the cooling demand, these results only refer to the cooling power of the mechanical ventilation system, as the studied room cases do not have cooling units. As can be seen in Figures 9-12, the different orientations do not follow steady trends in terms of highest and lowest cooling peaks, with the exception of the North-oriented window cases, which always have the lowest peaks and are not affected by the use of shading. In most of the other cases, shading reduces the peak load to variable extents.
Glazing types A, B and D have almost the same results when shading is not used, so only glazing type B is displayed, see Figures 9-10. The implementation of shading, however, has a different effect on glazing type A compared to the other two types, which perform similarly, compare Figure 10 and Figure 13.
Glazing type C results in slightly lower cooling peaks than the other types, with a noticeable reduction in the cooling peak of the case with a 10% WFR on the South. When shading is implemented, this glazing type does not follow the same trend as the others, see Figure 12. When the WFR is 10%, the results are lower for all orientations compared to the same cases with other glazing types.

### 5.1.5 Electricity for lighting

All glazing types resulted in a very similar electricity demand for lighting, which additionally was not significantly affected by the use of shading. Therefore, only the results from glazing type B are displayed and are representative of all cases, see Figure 14.

![Glazing type B: U=1.00 W/m²K, g=0.51, Tvis=0.75](image)

*Figure 14. Annual electricity demand for lighting in building cases with glazing type B: U=1.00 W/m²K, g=0.51, Tvis=0.75, without shading.*

It is evident that West-oriented windows result in the lowest electricity demand for lighting. A 10% WFR on the West reduces the electricity demand by 36% (3.1 kWh/m²yr) compared to the windowless case. Increasing the window size, on any orientation, does not result in an analogous decrease in the electricity demand for lighting. A 30% WFR on the West results in a 48% (4.2 kWh/m²yr) reduction in the electricity demand compared to the windowless case.

### 5.1.6 Total energy

In all cases, there is a steady trend where the South-oriented cases result in the lowest energy demand, followed by the East, then the West and finally the North, see Figures 15-18. Note that no energy factor or coefficient of performance are applied to these results, i.e. each kWh is weighted by factor 1, regardless of end-use (heating, cooling or lighting). Increasing the glazing size seems to have a stronger impact on all other orientations besides the South. The use of shading has a very small impact on these results, so the relevant graphs have been omitted.
5.1.6.1 **Glazing type A: U=1.10 W/m²K, g=0.64, T_{vis}=0.81**

Figure 15 clearly shows that most window cases increase the total energy demand compared to the windowless cases. Only the cases with a 10% WFR on the South or West reduce the demand compared to the windowless cases, by 10% (5.7 kWh/m² yr) and 2% (1.2 kWh/m² yr).
respectively. The case with a 30% WFR on the South has the same energy demand as the windowless case. The North-oriented cases, which have the highest energy demand, increase the demand by 6% (3.3 kWh/m²yr) when the WFR is 10% and by 29% (16.7 kWh/m²yr) when the WFR is 30%, compared to the equivalent windowless case.

5.1.6.2 Glazing type B: $U=1.00 \text{ W/m}^2\text{K}$, $g=0.51$, $T_{vis}=0.75$

This glazing type performs almost the same as glazing type A, but all values are slightly higher, see Figure 16. Only the case with a 10% WFR on the South manages to reduce the energy demand compared to the windowless case - by 8% (4.2 kWh/m²yr). A 30% WFR on the South yields a slightly higher demand than the windowless case.

5.1.6.3 Glazing type C: $U=1.00 \text{ W/m}^2\text{K}$, $g=0.30$, $T_{vis}=0.61$

The window cases with this glazing type result in the highest total energy demand compared to all other glazing types, see Figure 17. A 10% WFR on the South results in the same energy demand as the equivalent windowless case, and all other window cases have a higher demand. Additionally, increasing the glazing size causes a higher increase in the energy demand compared to the other glazing types. When oriented towards the North, a 10% WFR causes an 11% (6.4 kWh/m²yr) increase in the energy demand and a 30% WFR causes a 39% (22.03 kWh/m²yr) increase compared to the windowless case. A 10% WFR on the South with this glazing type results in a slightly higher energy demand than a 30% WFR on the South with glazing type A.

5.1.6.4 Glazing type D: $U=0.50 \text{ W/m}^2\text{K}$, $g=0.50$, $T_{vis}=0.65$

Figure 18 indicates that this glazing type has the lowest overall energy demand. Additionally, increasing the glazing size has a lighter impact than it does for the other glazing constructions. Both window sizes on the South evidently reduce the energy demand compared to the windowless case, although the case with a 10% WFR requires slightly less energy than the case with a 30% WFR. A 10% WFR on the South results in a 13% (6.9 kWh/m²yr) energy demand reduction compared to the windowless case. The cases with a 10% WFR on the East and West also reduce the energy demand compared to their windowless equivalents, albeit slightly. The cases with a 30% WFR on the North and East yield the same energy demand as their respective 10% WFR versions with glazing type C.

5.1.7 Overheating

For the purposes of this study, overheating is measured in annual hours when the operative temperature of the simulated rooms is above 25$^\circ$ C. Since there is no cooling system in the room that adjusts to meet operative temperature requirements, overheating hours are used to evaluate the indoor thermal comfort in each case. Figures 19-26 show the annual overheating hours for each of the building cases with and without shading.
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Figure 19. Annual overheating hours (>25°C) for building cases with glazing type A: U=1.10 W/m²K, g=0.64, \( T_{vis}=0.81 \), without shading.

Figure 20. Annual overheating hours (>25°C) for building cases with glazing type A: U=1.10 W/m²K, g=0.64, \( T_{vis}=0.81 \), with shading.

Figure 21. Annual overheating hours (>25°C) for building cases with glazing type B: U=1.00 W/m²K, g=0.51, \( T_{vis}=0.75 \), without shading.

Figure 22. Annual overheating hours (>25°C) for building cases with glazing type B: U=1.00 W/m²K, g=0.51, \( T_{vis}=0.75 \), with shading.
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Figure 23. Annual overheating hours (>25°C) for building cases with glazing type C: U=1.00 W/m²K, g=0.30, $T_{vis}=0.61$, without shading.

Figure 24. Annual overheating hours (>25°C) for building cases with glazing type C: U=1.00 W/m²K, g=0.30, $T_{vis}=0.61$, with shading.

Figure 25. Annual overheating hours (>25°C) for building cases with glazing type D: U=0.50 W/m²K, g=0.50, $T_{vis}=0.65$, without shading.

Figure 26. Annual overheating hours (>25°C) for building cases with glazing type D: U=0.50 W/m²K, g=0.50, $T_{vis}=0.65$, with shading.
It is evident from Figures 19-26 that shading plays a significant role in reducing the overheating hours. With the use of shading, it seems that glazing type D ($U=0.50 \text{ W/m}^2\text{K}$, $g=0.50$, $T_{\text{vis}}=0.65$) performs the best – even better than glazing type C ($U=1.00 \text{ W/m}^2\text{K}$, $g=0.30$, $T_{\text{vis}}=0.61$), which has a significantly lower $g$-value. When the WFR is up to 10%, shading completely eliminates overheating.

Orientation has a large impact on the results. North-oriented building cases have no problem with overheating, while South and West orientations result in the most overheating hours. In most unshaded building cases - except those with glazing type A ($U=1.10 \text{ W/m}^2\text{K}$, $g=0.64$, $T_{\text{vis}}=0.81$) - when the WFR is 10%, only the West-oriented cases result in overheating. When the WFR increases to 30%, the South-oriented cases show an acute increase in overheating hours, surpassing those of the West-oriented cases, refer to Figure 21, Figure 23 and Figure 25.

Glazing type A ($U=1.10 \text{ W/m}^2\text{K}$, $g=0.64$, $T_{\text{vis}}=0.81$) results in the largest amount of overheating hours, both with and without shading, compared to the other glazing types. See Figures 19-20. However, even in the worst case – a 30% WFR with glazing type A on the South – the overheating hours are only 125 in a whole year, which corresponds to 1.4% of the time or 5.7% of the summer season.

Comparing glazing types B ($U=1.00 \text{ W/m}^2\text{K}$, $g=0.51$, $T_{\text{vis}}=0.75$) and D ($U=0.50 \text{ W/m}^2\text{K}$, $g=0.50$, $T_{\text{vis}}=0.65$) - see Figures 21-22 and Figures 25-26 – it is evident that they perform similarly when used without shading, but the South-oriented cases perform quite differently when shading is implemented. Shading eliminates the overheating hours in the South-oriented cases with glazing type D, but not in the cases with glazing type C.

### Daylight

The daylight exposure of each of the building cases was measured in terms of average illuminance and maximum illuminance on a horizontal surface located 0.6m above the floor, based on the annual hourly results. The average illuminance was calculated for daytime hours only. As can be seen in Figures 27-34, the average daylight levels are not significantly affected by the different glazing properties, although there is a slight decrease in the results with lower $T_{\text{vis}}$ percentages, compare Figure 27 and Figure 31. Glazing types A ($U=1.10 \text{ W/m}^2\text{K}$, $g=0.64$, $T_{\text{vis}}=0.81$) and B ($U=1.00 \text{ W/m}^2\text{K}$, $g=0.51$, $T_{\text{vis}}=0.75$) have the highest average daylight levels, while types C ($U=1.00 \text{ W/m}^2\text{K}$, $g=0.30$, $T_{\text{vis}}=0.61$) and D ($U=0.50 \text{ W/m}^2\text{K}$, $g=0.50$, $T_{\text{vis}}=0.65$) the lowest. The daylight levels vary according to orientation, and are highest on the South, followed by the West, the East and finally the North. On the South, most 10% WFR cases without shading result in an average illuminance in the range of 500 lux, while the 30% WFR cases yield approximately 1500 lux. The use of shading appears to mainly affect the South-oriented cases. The case with a 30% WFR on the South with glazing type A is affected the most by the use of shading, which reduces the average illuminance from 1766 lux to 1047 lux.
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Figure 27. Average daylight levels in the building cases with glazing type A: $U=1.10 \text{ W/m}^2\text{K}$, $g=0.64$, $T_{vis}=0.81$, without shading.

Figure 28. Average daylight levels in the building cases with glazing type A: $U=1.10 \text{ W/m}^2\text{K}$, $g=0.64$, $T_{vis}=0.81$, with shading.

Figure 29. Average daylight levels in the building cases with glazing type B: $U=1.00 \text{ W/m}^2\text{K}$, $g=0.51$, $T_{vis}=0.75$, without shading.

Figure 30. Average daylight levels in the building cases with glazing type B: $U=1.00 \text{ W/m}^2\text{K}$, $g=0.51$, $T_{vis}=0.75$, with shading.
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Figure 31. Average daylight levels in the building cases with glazing type C: $U=1.00 \text{ W/m}^2\text{K}$, $g=0.30$, $T_{vis}=0.61$, without shading.

Figure 32. Average daylight levels in the building cases with glazing type C: $U=1.00 \text{ W/m}^2\text{K}$, $g=0.30$, $T_{vis}=0.61$, with shading.

Figure 33. Average daylight levels in the building cases with glazing type D: $U=0.50 \text{ W/m}^2\text{K}$, $g=0.50$, $T_{vis}=0.65$, without shading.

Figure 34. Average daylight levels in the building cases with glazing type D: $U=0.50 \text{ W/m}^2\text{K}$, $g=0.50$, $T_{vis}=0.65$, with shading.
Figures 35-38 display the maximum illuminance values recorded in the different building cases over the course of a year. The use of shading has a negligible effect on these results, so the relevant graphs have been omitted.

**Figure 35.** Maximum daylight levels in the building cases with glazing type A: $U=1.10 \text{ W/m}^2\text{K}$, $g=0.64$, $T_{vis}=0.81$, without shading.

**Figure 36.** Maximum daylight levels in the building cases with glazing type B: $U=1.00 \text{ W/m}^2\text{K}$, $g=0.51$, $T_{vis}=0.75$, without shading.

**Figure 37.** Maximum daylight levels in the building cases with glazing type C: $U=1.00 \text{ W/m}^2\text{K}$, $g=0.30$, $T_{vis}=0.61$, without shading.

**Figure 38.** Maximum daylight levels in the building cases with glazing type D: $U=0.50 \text{ W/m}^2\text{K}$, $g=0.50$, $T_{vis}=0.65$, without shading.
It is evident that the glazing type affects the maximum more than the average illuminance values. The North-oriented building cases have significantly lower maximum daylight values compared to the other orientations. Finally, when the WFR is 10%, the South, West and East orientations result in very similar maximum illuminance values, but these differ when the WFR increases to 30%.
5.2 45°-window geometry

5.2.1 Heating demand

Similar to the 90°-window results, South-oriented cases have the lowest heating demand, followed by the West and East and finally the North. See Figures 39-42. Again, shading has a negligible effect on the results, so the relevant graphs have been excluded from this section and can be found in the appendix.

Figure 39. Annual heating energy demand for building cases with glazing type A: $U=1.10 \text{ W/m}^2\text{K}$, $g=0.64$, $T_{vis}=0.81$.

Figure 40. Annual heating energy demand for building cases with glazing type B: $U=1.00 \text{ W/m}^2\text{K}$, $g=0.51$, $T_{vis}=0.75$.

Figure 39. Annual heating energy demand for building cases with glazing type A: $U=1.10 \text{ W/m}^2\text{K}$, $g=0.64$, $T_{vis}=0.81$.

Figure 40. Annual heating energy demand for building cases with glazing type B: $U=1.00 \text{ W/m}^2\text{K}$, $g=0.51$, $T_{vis}=0.75$. 
5.2.1.1 Glazing type A: U=1.10 W/m²K, g=0.64, T_{vis}=0.81

Figure 39 shows that adding a 10% glazed area on the South causes almost no increase in the heating demand. However, increasing the glazed area to 30% causes an 85% (14.7 kWh/m²yr) increase in the heating demand, compared to the windowless case. On the North, the small and large window cases cause a significant increase in the heating demand. A 10% WFR on the North results in a 23% (8.4 kWh/m²yr) higher heating demand, while 30% WFR on the North almost doubles the heating demand compared to the windowless case, increasing it by 85% (30.6 kWh/m²yr).

5.2.1.2 Glazing type B: U=1.00 W/m²K, g=0.51, T_{vis}=0.75

Comparing Figure 39 and Figure 40 it is apparent that the building cases with glazing type B have very a similar heating demand to the equivalent cases with glazing type A. The results are only slightly higher with glazing type B.

5.2.1.3 Glazing type C: U=1.00 W/m²K, g=0.30, T_{vis}=0.61

The building cases with this glazing type result in the highest overall heating demand, see Figure 41. Even on the South, a 10% glazed area results in an 18% (5.8 kWh/m²yr) increase of the heating demand compared to the same building case without a window, while a 30% glazed area results in a 73% (23.8 kWh/m²yr) increase. On the North, where the maximum heating demands occur, a 10% glazed area causes a 33% (11.9 kWh/m²yr) increase and a 30% glazed area results in a doubling of the heating demand compared to the windowless case (103% - 37.2 kWh/m²yr higher demand).

5.2.1.4 Glazing type D: U=0.50 W/m²K, g=0.50, T_{vis}=0.65

This glazing type results in the lowest overall heating demand. Figure 42 clearly shows that the building case with 10% glazing on the South has a lower heating demand than the equivalent windowless case. A 30% glazed area on the South increases the heating demand negligibly compared to the windowless case. Note also that on the South, a 30% WFR with glazing type D results in an 11% (4.4 kWh/m²yr) lower heating demand than a 10% WFR with glazing type C. The case with 10% glazing on the West also causes an almost negligible increase in the heating demand. The worst performing orientation is again the North, where a 10% WFR results in a 7% (2.6 kWh/m²yr) increase in the heating demand and a 30% WFR results in a 35% (12.8 kWh/m²yr) increase in the heating demand, compared to the windowless case.

5.2.2 Heating power

Glazing types A, B and C yield very similar results, so only those related to glazing type B are displayed in Figure 43. Figure 44 shows the resulting heating peak loads in the building cases with glazing type D, which were generally lower. For example, 10% glazing on the South with glazing type B results in a peak load which is 14% (5.2 W/m²) higher than that of
the windowless case, whereas the same window case with glazing type D results in an 8% (2.9 W/m²) higher peak, compared to the windowless case. In the 30% WFR category, again on the South, glazing type B increases the peak load by 44% (16 W/m²) compared to the case with no window, while glazing type D increases it by 26% (9.4 W/m²).

In all cases, changing the window orientation has no effect on the results. In addition, the use of insulated shading proved to cause a negligible reduction of the heating peak loads, so the relevant graphs have not been included in this chapter.

5.2.3 Cooling demand

These results refer to the cooling demand of the mechanical ventilation system, as the studied rooms do not have space cooling. The cooling demand does not vary much for the different glazing types, and the use of shading has a negligible effect on the results. Additionally, all orientations except the North perform similarly. Figure 45 displays the cooling demand for the cases with glazing type B, and the results are more or less representative of all glazing types. It seems that increasing the window area from 10% to 30% barely increases the cooling demand for all orientations except the North. On the North, a 10% WFR results in a 5% (0.4 kWh/m²yr) increase in the cooling demand compared to the windowless case, while a 30% WFR results in an 11% (0.9 kWh/m²yr) increase.

Figure 43. Maximum heating power required by building cases with glazing type B: U=1.00 W/m²K, g=0.51, T_{vis}=0.75.

Figure 44. Maximum heating power required by building cases with glazing type D: U=0.50 W/m²K, g=0.50, T_{vis}=0.65.
5.2.4 Cooling power

Similarly to the cooling demand, the results presented in this section only refer to the cooling power of the mechanical ventilation system, as the studied rooms do not have space cooling. The cooling power peak loads are generally lower for North-oriented windows, especially in the 10% WFR cases, see Figure 46. For all glazing types except C, increasing the glazed area from 10% to 30% does not result in a significant increase in the peak load, unless the window is oriented towards the North, see Figure 48. Shading plays a role in reducing the peak load, but mainly in the 10% WFR category, see Figure 47 and Figure 49. The building cases with glazing type C are the only ones where window size affects the results on all orientations and where shading has a negligible effect on the peak loads.

Figure 45. Annual cooling energy demand for building cases with glazing type B: $U=1.00 \text{ W/m}^2\text{K}$, $g=0.51$, $T_{\text{vis}}=0.75$, without shading.
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Figure 46. Maximum cooling power required by building cases with glazing type B: \( U=1.00 \, \text{W/m}^2\text{K}, \, g=0.51, \, T_{vis}=0.75 \) without shading.

Figure 47. Maximum cooling power required by building cases with glazing type B: \( U=1.00 \, \text{W/m}^2\text{K}, \, g=0.51, \, T_{vis}=0.75 \) with shading.

Figure 48. Maximum cooling power required by building cases with glazing type C: \( U=1.00 \, \text{W/m}^2\text{K}, \, g=0.30, \, T_{vis}=0.61 \) without shading.

Figure 49. Maximum cooling power required by building cases with glazing type C: \( U=1.00 \, \text{W/m}^2\text{K}, \, g=0.30, \, T_{vis}=0.61 \) with shading.
5.2.5 Electricity for lighting

The results show that there was no significant variation in the electricity demand for lighting between the cases with the different glazing types, so only the results for glazing type B are presented in Figure 50, which can be considered representative of all cases. In addition, note that the use of shading had a negligible effect on the electricity use for lights, so these graphs have been omitted.

![Graph showing electricity demand for lighting in building cases with glazing type B](image.png)

*Figure 50. Annual electricity demand for lighting in building cases with glazing type B: $U=1.00\ W/m^2K$, $g=0.51$, $T_{\text{vis}}=0.75$, without shading.*

Figure 50 shows that orienting the windows towards the West results in the lowest electricity demand compared to the other orientations. The second lowest electricity demand occurs on the South, then on the North and finally the East. When the window is oriented towards the West, a 10% WFR results in a 38% (3.3 kWh/m²yr) reduction of the electricity demand, while a 30% WFR results in a slightly higher reduction of 50% (4.4 kWh/m²yr), compared to the windowless case.

5.2.6 Total energy

Orientation clearly affects the total energy demand of the different building cases. Those facing South always have the lowest demand, followed by the West-oriented cases, then the East and finally the North, see Figures 51-54. Note that no energy factor or coefficient of performance are applied to these results, i.e. each kWh is weighted by factor 1, regardless of end-use (heating, cooling or lighting). Window size plays an important role in increasing the total energy demand in most cases. Shading did not prove to have a significant effect on the results, so the relevant graphs are not included in this chapter.
Figure 51. Total annual energy demand for building cases with glazing type A: \( U = 1.10 \text{ W/m}^2\text{K}, \ g = 0.64, \ T_{\text{vis}} = 0.81 \).

Figure 52. Total annual energy demand for building cases with glazing type B: \( U = 1.00 \text{ W/m}^2\text{K}, \ g = 0.51, \ T_{\text{vis}} = 0.75 \).

Figure 53. Total annual energy demand for building cases with glazing type C: \( U = 1.00 \text{ W/m}^2\text{K}, \ g = 0.30, \ T_{\text{vis}} = 0.61 \).

Figure 54. Total annual energy demand for building cases with glazing type D: \( U = 0.50 \text{ W/m}^2\text{K}, \ g = 0.50, \ T_{\text{vis}} = 0.65 \).

5.2.6.1 Glazing type A: \( U = 1.10 \text{ W/m}^2\text{K}, \ g = 0.64, \ T_{\text{vis}} = 0.81 \)

Figure 51 shows that the South-oriented building case with a 10% WFR has a slightly lower energy demand than the windowless case. Specifically, the case with 10% glazed area has a 3% (1.7 kWh/m\(^2\text{yr}\)) lower demand. On the other hand, a 30% WFR on the South results in a 23% (11.5 kWh/m\(^2\text{yr}\)) higher energy demand than the windowless case with. On the North,
where the energy demand is highest, a 10% WFR results in an 11% (5.9 kWh/m² yr) increase, while a 30% WFR results in a 52% (27.4 kWh/m² yr) increase compared to the windowless case.

5.2.6.2 Glazing type B: U=1.00 W/m² K, g=0.51, T_{vis}=0.75

This glazing type yields similar results to glazing type A, see Figure 51 and Figure 52. Again, the case with a 10% WFR on the South has a slightly lower energy demand than the windowless case, although in this case the difference is even smaller.

5.2.6.3 Glazing type C: U=1.00 W/m² K, g=0.30, T_{vis}=0.61

It is apparent from Figures 51-54 that the building cases with glazing type C have the highest overall energy demand. A 10% glazed area oriented towards the South results in an 8% (3.8 kWh/m² yr) higher energy demand than the windowless case and a 30% glazed area on the South results in a 42% (20.8 kWh/m² yr) higher demand. When oriented towards the North, a 10% WFR increases the energy demand by 18% (9.5 kWh/m² yr) compared to the windowless case, while a 30% WFR increases it by 64% (33.8 kWh/m² yr).

5.2.6.4 Glazing type D: U=0.50 W/m² K, g=0.50, T_{vis}=0.65

This glazing type results in the lowest overall energy demand. Both the 10% and the 30% WFR on the South have a lower energy demand than the equivalent windowless case, see Figure 54. The case with a 10% glazed area on the South results in an 11% (5.4 kWh/m² yr) lower energy demand and the case with a 30% glazed area results in a 3% (1.7 kWh/m² yr) lower demand. Note that this case, 30% WFR on the South, yields the same total energy demand as the case with a 10% WFR on the South with glazing type A. With glazing type D, a 10% WFR on the East and West also reduces the energy demand compared to the windowless cases. On the North, the energy demand increases only slightly compared to the windowless case with a 10% WFR. When the WFR is 30% WFR, the results from glazing type D are lower than those from a 10% WFR with glazing type C. On the South for example, 30% window area with glazing type D results in a 10% (5.5 kWh/m² yr) lower energy demand than a 10% WFR with glazing type C.

5.2.7 Overheating

For the purposes of this study, overheating is measured in annual hours when the operative temperature of the simulated rooms is above 25°C. Since there is no adaptive cooling system in the room, overheating are used to evaluate the indoor thermal comfort in each case. Figures 55-62 show the annual overheating hours for each of the building cases with and without shading.
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Figure 55. Annual overheating hours (>25°C) for building cases with glazing type A: $U=1.10 \text{ W/m}^2\text{K}$, $g=0.64$, $T_{vis}=0.81$, without shading.

Figure 56. Annual overheating hours (>25°C) for building cases with glazing type A: $U=1.10 \text{ W/m}^2\text{K}$, $g=0.64$, $T_{vis}=0.81$, with shading.

Figure 57. Annual overheating hours (>25°C) for building cases with glazing type B: $U=1.00 \text{ W/m}^2\text{K}$, $g=0.51$, $T_{vis}=0.75$, without shading.

Figure 58. Annual overheating hours (>25°C) for building cases with glazing type B: $U=1.00 \text{ W/m}^2\text{K}$, $g=0.51$, $T_{vis}=0.75$, with shading.

Glazing type A:
$U=1.10 \text{ W/m}^2\text{K}$, $g=0.64$, $T_{vis}=0.81$

- no shading
  - South • • • North
  - East • • • West

Glazing type A:
$U=1.10 \text{ W/m}^2\text{K}$, $g=0.64$, $T_{vis}=0.81$

- with shading
  - South • • • North
  - East • • • West

Glazing type B:
$U=1.00 \text{ W/m}^2\text{K}$, $g=0.51$, $T_{vis}=0.75$

- no shading
  - South • • • North
  - East • • • West

Glazing type B:
$U=1.00 \text{ W/m}^2\text{K}$, $g=0.51$, $T_{vis}=0.75$

- with shading
  - South • • • North
  - East • • • West
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Figure 59. Annual overheating hours (>25°C) for building cases with glazing type C: U=1.00 W/m²K, g=0.30, T_vis=0.61, without shading.

Figure 60. Annual overheating hours (>25°C) for building cases with glazing type C: U=1.00 W/m²K, g=0.30, T_vis=0.61, with shading.

Figure 61. Annual overheating hours (>25°C) for building cases with glazing type D: U=0.50 W/m²K, g=0.50, T_vis=0.65, without shading.

Figure 62. Annual overheating hours (>25°C) for building cases with glazing type D: U=0.50 W/m²K, g=0.50, T_vis=0.65, with shading.
Shading evidently has a significant mitigating effect on the overheating hours, especially when the WFR is up to 10%. Orientation also plays an important role in determining the overheating hours. The North-oriented building cases have the least overheating, while the South-oriented cases have the most. West-oriented cases have the second-highest numbers of overheating hours, after the South-oriented.

All glazing types seem to follow very similar trends, except for glazing type C (U=1.00 W/m²K, g=0.30, T\textsubscript{vis}=0.61), which has remarkably less overheating hours even without shading, especially in the 10% WFR category, see Figure 59. Glazing type A (U=1.10 W/m²K, g=0.64, T\textsubscript{vis}=0.81) yields the most overheating, see Figures 55-56. However, even the worst case – 30% WFR on the South with glazing type A – results in only 213 hours per year where the indoor temperature is above 25°C, which corresponds to 2.4% of the time, or 9.7% of the summer season.

5.2.8 Daylight

The average and maximum illuminance are not significantly affected by the different glazing properties. Glazing types A (U=1.10 W/m²K, g=0.64, T\textsubscript{vis}=0.81) and B (U=1.00 W/m²K, g=0.51, T\textsubscript{vis}=0.75) had very similar results, so only glazing type A is presented in Figures 63-64, while the results from glazing types C (U=1.00 W/m²K, g=0.30, T\textsubscript{vis}=0.61) and D (U=0.50 W/m²K, g=0.50, T\textsubscript{vis}=0.65), which were also similar, are represented by glazing type C in Figures 65-66. The first two have slightly higher daylight levels than the second two.

It is evident that shading significantly reduces the daylight levels, especially when the window is oriented towards the South and even more when the WFR is 30%. In the South-oriented 30% WFR case with glazing type A, the use of shading reduces the average illuminance from 2546 lux to 1229 lux. North-oriented building cases are not affected by the use of shading. Orientation plays an important role in determining the daylight availability. The South-oriented cases always have the highest average values, followed by the West, then the East and finally the North. On the South, the average daylight levels are between 709 lux and 880 lux when the WFR is 10%, and between 1950 and 2546 lux when the WFR is 30%.
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Glazing type A:
U=1.10 W/m²K, g=0.64, T_{vis}=0.81
no shading

- South • • • North
- East - • West

Figure 63. Average daylight levels in the building cases with glazing type A: U=1.10 W/m²K, g=0.64, T_{vis}=0.81, without shading.

Glazing type A:
U=1.10 W/m²K, g=0.64, T_{vis}=0.81
with shading

- South • • • North
- East - • West

Figure 64. Average daylight levels in the building cases with glazing type A: U=1.10 W/m²K, g=0.64, T_{vis}=0.81, with shading.

Glazing type C:
U=1.00 W/m²K, g=0.30, T_{vis}=0.61
no shading

- South • • • North
- East - • West

Figure 65. Average daylight levels in the building cases with glazing type C: U=1.00 W/m²K, g=0.30, T_{vis}=0.61, without shading.

Glazing type C:
U=1.00 W/m²K, g=0.30, T_{vis}=0.61
with shading

- South • • • North
- East - • West

Figure 66. Average daylight levels in the building cases with glazing type C: U=1.00 W/m²K, g=0.30, T_{vis}=0.61, with shading.
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Figure 67-Figure 70 display the maximum illuminance values in the different building cases. Shading did not affect these values, so the relevant graphs are not included in this chapter.

![Figure 67](image1)

**Figure 67. Maximum daylight levels in the building cases with glazing type A: U=1.10 W/m²K, g=0.64, T\text{vis}=0.81, without shading.**

![Figure 68](image2)

**Figure 68. Maximum daylight levels in the building cases with glazing type B: U=1.00 W/m²K, g=0.51, T\text{vis}=0.75, without shading.**

![Figure 69](image3)

**Figure 69. Maximum daylight levels in the building cases with glazing type C: U=1.00 W/m²K, g=0.30, T\text{vis}=0.61, without shading.**

![Figure 70](image4)

**Figure 70. Maximum daylight levels in the building cases with glazing type D: U=0.50 W/m²K, g=0.50, T\text{vis}=0.65, without shading.**

Orientation has a significant impact on the maximum daylight levels. When the WFR is 10%, the South, East and West orientations have similar maximum values, but these begin to vary
more as the WFR increases to 30%. Generally, the average and maximum illuminance results follow the same trends, with the exception of the results from the North-oriented cases, which have much lower maximum values compared to the other orientations.
5.3 15°-window geometry

5.3.1 Heating demand

Figures 71-74 show a similar trend in the results, where the South-oriented cases have the lowest heating demand, followed by the West, then the East and finally the North, although the difference between the orientations is small. Increasing the window size has a strong impact on the resulting heating demand, except when glazing type D is used, see Figure 74. The use of shading has a negligible effect on the results, so the relevant graphs have been excluded from this chapter.

Figure 71. Annual heating energy demand for building cases with glazing type A: $U=1.10$ W/m²K, $g=0.64$, $T_{vis}=0.81$.

Figure 72. Annual heating energy demand for building cases with glazing type B: $U=1.00$ W/m²K, $g=0.51$, $T_{vis}=0.75$. 
5.3.1.1 Glazing type A: \( U=1.10 \text{ W/m}^2\text{K}, \ g=0.64, \ T_{\text{vis}}=0.81 \)

Figure 71 clearly shows that all window cases result in a higher heating demand than the windowless cases. A 10% WFR on the South yields a 13% (4.7 kWh/m²yr) increase in the heating demand compared to the windowless case. The case with a 30% WFR on the South results in a 65% (23.4 kWh/m²yr) increase. When the window is oriented towards the North, a 10% WFR results in a 17% (6.4 kWh/m²yr) higher heating demand, while a 30% WFR results in a 74% (28.2 kWh/m²yr) higher demand compared to the windowless case.

5.3.1.2 Glazing type B: \( U=1.00 \text{ W/m}^2\text{K}, \ g=0.51, \ T_{\text{vis}}=0.75 \)

The resulting heating demand from using glazing type B is very similar to that previously described for glazing type A. All values are only slightly higher, see Figure 71 and Figure 72.

5.3.1.3 Glazing type C: \( U=1.00 \text{ W/m}^2\text{K}, \ g=0.30, \ T_{\text{vis}}=0.61 \)

This glazing type results in the highest overall heating demand, see Figure 73. In the building cases with South-oriented windows, 10% WFR results in a 25% (8.8 kWh/m²yr) higher heating demand, while 30% glazed area results in an 84% (30 kWh/m²yr) higher demand compared to the windowless case. When the window is oriented towards the North, 10% WFR results in a 27% (10.2 kWh/m²yr) higher heating demand, while a 30% WFR results in a 90% (34.5 kWh/m²yr) higher demand compared to the windowless case.

5.3.1.4 Glazing type D: \( U=0.50 \text{ W/m}^2\text{K}, \ g=0.50, \ T_{\text{vis}}=0.65 \)

This glazing type results in the lowest overall heating demand, and as Figure 74 indicates, window size does not affect the results as much as with the other glazing types. The building cases with a 10% WFR on the South, West and East result in almost the same heating demand.
as their equivalent windowless cases, with the window cases having a slightly lower demand. The case with 10% WFR on the North increases the demand compared to the windowless case, but only slightly. When the WFR is increased to 30% and the window is oriented towards the South, the resulting heating demand is 20% (7.2 kWh/m²yr) higher than for the equivalent windowless case. If the window is oriented towards the North, then the heating demand increases by 28% (10.7 kWh/m²yr) compared to the windowless case. On all orientations except North, a 30% WFR with glazing type D results in a lower heating demand than a 10% WFR with glazing type C.

5.3.2 Heating power

The maximum heating power is similar for most glazing types, except type D, where it is much lower, see Figures 75-76. Figure 75 displays the results for glazing type B, which are similar to the results obtained with glazing types A and C. It is apparent that orientation has no impact on the results. In addition, the use of shading also has a negligible effect on the results, so the relevant graphs have been omitted.

Figure 75. Maximum heating power required by building cases with glazing type B: U=1.00 W/m²K, g=0.51, T_{vis}=0.75

Figure 76. Maximum heating power required by building cases with glazing type D: U=0.50 W/m²K, g=0.50, T_{vis}=0.65

A 10% WFR on the South, with glazing type B results in a 14% (5.2 W/m²) higher peak load than the equivalent windowless case. If glazing type D is used in the same building case, then the heating peak load is only 8% (2.9 W/m²) higher than the windowless case. When the WFR is 30%, glazing type B on the South results in a 44% (16.5 W/m²) higher peak load, while glazing type D on the South results in a 26% (9.7 W/m²) higher peak load compared to the windowless case.
5.3.3 Cooling demand

These results refer to the cooling demand of the mechanical ventilation system, as the studied rooms do not have space cooling. The cooling demand does not vary much for the different glazing types, and the use of shading has a negligible effect on the results. Therefore, only the results for glazing type B are displayed, in Figure 77, and they are considered representative of all glazing types. Orientation also proved to have a negligible effect on the results. Only the building cases oriented towards the North have a slightly lower cooling demand, and only in the 10% WFR category.

![Figure 77. Annual cooling energy demand for building cases with glazing type B: U=1.00 W/m²K, g=0.51, Tvis=0.75](image)

Increasing the glazed area from 0% to 10% results in an increase in the cooling demand – 12% (0.9 kWh/m²yr) on the South. A further increase of the glazed area to 30% does not bring forth a similar increase in the cooling demand. On the South, a 30% WFR has the same cooling demand as a 10% WFR.

5.3.4 Cooling power

Similarly to the cooling demand, these results only refer to the cooling power of the mechanical ventilation system, as the studied rooms do not have space cooling. The cooling peak loads are very similar for the building cases with glazing types A, B and D, so only one of them is displayed in Figure 78. The peak loads of the building cases with glazing type C follow a different trend, as shown in Figure 79. In all glazing cases, the highest peaks occur when the window is oriented towards the South, followed by the West, then the East and finally the North, although these differences disappear when the WFR is 30%. The use of shading does affect the results, but slightly. Compare Figures 78-79 to Figures 80-81.
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Figure 78. Maximum cooling power required by building cases with glazing type B: \( U = 1.00 \text{ W/m}^2\text{K}, \ g = 0.51, \ T_{vis} = 0.75 \) without shading.

Figure 79. Maximum cooling power required by building cases with glazing type B: \( U = 1.00 \text{ W/m}^2\text{K}, \ g = 0.51, \ T_{vis} = 0.75 \) with shading.

Figure 80. Maximum cooling power required by building cases with glazing type C: \( U = 1.00 \text{ W/m}^2\text{K}, \ g = 0.30, \ T_{vis} = 0.61 \) without shading.

Figure 81. Maximum cooling power required by building cases with glazing type C: \( U = 1.00 \text{ W/m}^2\text{K}, \ g = 0.30, \ T_{vis} = 0.61 \) with shading.
The building case with a 10% WFR on the South with glazing type B has a 37% (6.4 W/m²) higher peak load than the equivalent windowless case. Increasing the WFR to 30% does not further increase the peak load significantly. A 10% WFR on the North with glazing type B results in a 25% (4.4 W/m²) higher peak load compared to the windowless case. The use of shading reduces these peak loads, mainly in the 10% WFR category. The building cases with glazing type C have the same peak loads as those with glazing type B in the 30% WFR category, but lower peak loads in the 10% WFR category. A 10% WFR on the South with glazing type C results in a 19% (3.3 W/m²) higher peak than the windowless case, while a 10% WFR on the North with glazing type C results in a 11% (1.8 W/m²) higher peak than the windowless case.

5.3.5 Electricity for lighting

The electricity demand for lighting proved to be almost the same regardless of glazing type, so only the results for glazing type B are displayed, see Figure 82. The window orientation that results in the lowest lighting demand is the West, followed by the South, then the North and finally the East. When the window is oriented towards the West, a 10% WFR results in a 36% (3.2 kWh/m²yr) lower electricity demand for lighting compared to the windowless case. A 30% WFR on the West results in a slightly lower demand – 49% (4.3 kWh/m²yr) lower than the windowless case. The use of shading caused an insignificant increase in the lighting demand, so these results have not been included in this chapter, but can be found in the appendix.

![Figure 82. Annual electricity demand for lighting in building cases with glazing type B: U=1.00 W/m²K, g=0.51, T_{vis}=0.75, without shading.](image)

5.3.6 Total energy

Figures 83-86 clearly show that the South-oriented building cases always have the lowest energy demand. The West orientations have the second lowest demand, followed by the East
and finally the North orientation. However, the variation in results between the different orientations is negligible. In all cases, the use of shading results in a negligible reduction of the total energy demand, so the relevant graphs are not displayed here.

**Figure 83.** Total annual energy demand for building cases with glazing type A: $U=1.10$ W/m$^2$K, $g=0.64$, $T_{vis}=0.81$.

**Figure 84.** Total annual energy demand for building cases with glazing type B: $U=1.00$ W/m$^2$K, $g=0.51$, $T_{vis}=0.75$.

**Figure 85.** Total annual energy demand for building cases with glazing type C: $U=1.00$ W/m$^2$K, $g=0.30$, $T_{vis}=0.61$.

**Figure 86.** Total annual energy demand for building cases with glazing type D: $U=0.50$ W/m$^2$K, $g=0.50$, $T_{vis}=0.65$. 
5.3.6.1 Glazing type A: $U=1.10 \text{ W/m}^2\text{K}$, $g=0.64$, $T_{vis}=0.81$

It is apparent from Figure 83 that a 10% WFR does not increase the total energy demand significantly compared to having no window. On the South, a 10% WFR results in an energy demand that is only 5% (2.5 kWh/m$^2$yr) higher than the windowless case. On the North, a 10% WFR results in an 8% (4.2 kWh/m$^2$yr) higher energy demand compared to the windowless case. When the WFR is 30%, a South-oriented window results in a 38% (20.1 kWh/m$^2$yr) higher energy demand, while a North-oriented window results in a 45% (25 kWh/m$^2$yr) higher energy demand compared to the equivalent windowless case.

5.3.6.2 Glazing type B: $U=1.00 \text{ W/m}^2\text{K}$, $g=0.51$, $T_{vis}=0.75$

The cases with glazing type B yield a similar energy demand to the cases with glazing type A, see Figure 83 and Figure 84. Glazing type B results in negligibly higher energy demand.

5.3.6.3 Glazing type C: $U=1.00 \text{ W/m}^2\text{K}$, $g=0.30$, $T_{vis}=0.61$

This glazing type results in the highest overall energy demand, see Figure 85. When the window is oriented towards the South, a 10% WFR results in a 13% (6.7 kWh/m$^2$yr) higher energy demand, while a 30% WFR results in a 51% (26.9 kWh/m$^2$yr) higher energy demand, compared to the windowless case. When the window is oriented towards the North, a 10% WFR results in a 15% (8 kWh/m$^2$yr) higher energy demand, while a 30% WFR results in a 57% (31.4 kWh/m$^2$yr) higher energy demand compared to the windowless case.

5.3.6.4 Glazing type D: $U=0.50 \text{ W/m}^2\text{K}$, $g=0.50$, $T_{vis}=0.65$

This glazing type results in the lowest overall energy demand, see Figure 86. All cases with a 10% WFR have a lower total energy demand than the equivalent windowless cases. On the South, the case with a 10% WFR has a 5% (2.4 kWh/m$^2$yr) lower energy demand than the equivalent windowless case. On the North, the case with a 10% WFR has a 2% (1 kWh/m$^2$yr) lower energy demand. In the 30% WFR category, a South-oriented window has an 8% (4 kWh/m$^2$yr) higher energy demand, while a North-oriented window has a 14% (7.6 kWh/m$^2$yr) higher energy demand compared to the windowless case.

5.3.7 Overheating

Figures 87-94 show the annual overheating hours for each of the building cases with and without shading.
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Glazing type A: U=1.10 W/m²K, g=0.64, T_{vis}=0.81
no shading

Glazing type B: U=1.00 W/m²K, g=0.51, T_{vis}=0.75
no shading

Glazing type A: U=1.10 W/m²K, g=0.64, T_{vis}=0.81
with shading

Glazing type B: U=1.00 W/m²K, g=0.51, T_{vis}=0.75
with shading

Figure 87. Annual overheating hours (>25°C) for building cases with glazing type A: U=1.10 W/m²K, g=0.64, T_{vis}=0.81, without shading.

Figure 88. Annual overheating hours (>25°C) for building cases with glazing type A: U=1.10 W/m²K, g=0.64, T_{vis}=0.81, with shading.

Figure 89. Annual overheating hours (>25°C) for building cases with glazing type B: U=1.00 W/m²K, g=0.51, T_{vis}=0.75, without shading.

Figure 90. Annual overheating hours (>25°C) for building cases with glazing type B: U=1.00 W/m²K, g=0.51, T_{vis}=0.75, with shading.
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Figure 91. Annual overheating hours (>25°C) for building cases with glazing type C: $U=1.00 \text{ W/m}^2\text{K}$, $g=0.30$, $T_{vis}=0.61$, without shading.

Figure 92. Annual overheating hours (>25°C) for building cases with glazing type C: $U=1.00 \text{ W/m}^2\text{K}$, $g=0.30$, $T_{vis}=0.61$, with shading.

Figure 93. Annual overheating hours (>25°C) for building cases with glazing type D: $U=0.50 \text{ W/m}^2\text{K}$, $g=0.50$, $T_{vis}=0.65$, without shading.

Figure 94. Annual overheating hours (>25°C) for building cases with glazing type D: $U=0.50 \text{ W/m}^2\text{K}$, $g=0.50$, $T_{vis}=0.65$, with shading.
It is evident that the implementation of shading significantly reduces overheating and completely eliminates it in the cases with a 10% WFR. The building cases with glazing types A (U=1.10 W/m²K, g=0.64, Tvis=0.81), B (U=1.00 W/m²K, g=0.51, Tvis=0.75) and D (U=0.50 W/m²K, g=0.50, Tvis=0.65) without shading have similar trends in their overheating hours, with the South orientation resulting in the most overheating hours when the WFR is 10%, and the West orientation reaching and surpassing the South, in terms of overheating hours, when the WFR is 30% of the floor area. The building cases with glazing type C (U=1.00 W/m²K, g=0.30, Tvis=0.61) without shading have the least overheating hours, especially when the WFR is 10%. With shading, all glazing types perform similarly. Glazing type A results in the most overheating. Orientation plays an important role in determining the overheating hours. The East and North-orientated cases have similar results - lower than those of the West and South - and are less affected by the use of shading. As mentioned before, the South-oriented cases have the most overheating when the WFR is 10%, but the West-oriented cases have slightly more overheating when the WFR is 30%.

5.3.8 Daylight

Figures 95-98 display the average illuminance values for the building cases with glazing type A (U=1.10 W/m²K, g=0.64, Tvis=0.81) and C (U=1.00 W/m²K, g=0.30, Tvis=0.61), which are considered representative of the results for glazing types B (U=1.00 W/m²K, g=0.51, Tvis=0.75) and D (U=0.50 W/m²K, g=0.50, Tvis=0.65) respectively.

In contrast to what was found for other window geometries, orientation does not affect the results significantly. Without shading, a 30% WFR with glazing type A on the South results in an average illuminance of 1385 lux, while the same case on the North results in 1241 lux. On the contrary, the use of shading and the glazing properties have an impact on the daylight levels, albeit limited. In the case with a 30% WFR ratio with glazing type A on the South, the use of shading reduces the average illuminance from 1385 lux to 1144 lux. The impact from shading is even smaller on the South-oriented 30% WFR case with glazing type C, where the average illuminance is reduced from 1150 lux to 1035 lux. Glazing type A, and by connection glazing type B, result in the highest average daylight levels, with and without shading.
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15°-window geometry

Figure 95. Average daylight levels in the building cases with glazing type A: U=1.10 W/m²K, g=0.64, T_{vis}=0.81, without shading.

Figure 96. Average daylight levels in the building cases with glazing type A: U=1.10 W/m²K, g=0.64, T_{vis}=0.81, with shading.

Figure 97. Average daylight levels in the building cases with glazing type C: U=1.00 W/m²K, g=0.30, T_{vis}=0.61, without shading.

Figure 98. Average daylight levels in the building cases with glazing type C: U=1.00 W/m²K, g=0.30, T_{vis}=0.61, with shading.
Figures 99-102 show the maximum daylight levels in each of the building cases without shading. The use of shading had no impact on the results.

Orientation seems to play a more significant role than glazing type. Glazing types A and B have slightly higher results, but in all glazing cases, the South, West and East orientations...
have very similar results. Only the North-oriented building cases have visibly lower maximum daylight levels.
6 Discussion

The results obtained by the simulations are discussed in this chapter and compared with the findings from previous studies, summarized in section 3.3, and the research hypotheses formulated in the beginning of this study, listed in section 3.4.

6.1 Heating demand

This study generally shows that the heating demand is clearly affected by orientation. The South-oriented cases always have the lowest heating demand, while the North has the highest and East and West orientations yield an intermediate heating demand. This is due to the increased solar access on the South, which allows for more passive solar heat gains, compensating for the heat losses, and in certain cases exceeding them. The West-oriented building cases have a lower heating demand than the East-oriented ones, and this is most likely because solar heat gains occur in the later part of the day when the window is on the West, which can mitigate the heating demand during the night. Therefore, in residential buildings in cold climates, windows should optimally be designed on the South or West. As expected, the variation in results between the different orientations is smaller as the window inclination becomes more horizontal. This is understandable, since smaller window inclinations result in more constant solar exposure among the different orientations.

The study also shows that the implementation of insulated shading results in a negligible reduction of the heating demand in all building cases, which was expected. Note that the insulated shading did not negatively affect the heating demand by obstructing solar gains, because it was activated during operative temperatures above 24° C, which did not occur during the heating season. It was also activated during the night, thus reducing night-time heat losses. However, this reduction was very small since the window U-value was only decreased by 5%.

Overall, the study proved that the best performing glazing type was D (U=0.50 W/m²K, g=0.50, T\text{vis}=0.65). This is due to its very low U-value in combination with an average g-value. As a result, heat losses were reduced to a minimum, while heat gains were still enabled. In contrast, the worst performing glazing type was C (U=1.00 W/m²K, g=0.30, T\text{vis}=0.61), and this is entirely due to its low g-value, which reduced passive solar heat gains. Glazing types A (U=1.10 W/m²K, g=0.64, T\text{vis}=0.81) and B (U=1.00 W/m²K, g=0.51, T\text{vis}=0.75) performed quite similarly, with type A resulting in a slightly lower heating demand. This is because they have almost the same U-value, but type A has a higher g-value, thus allowing more solar heat into the building.

One of the key findings of this study is that some building cases with windows managed to achieve a lower heating demand than the equivalent windowless cases. This mainly occurred when the WFR was 10% and the window was oriented towards the South. These results are in line with the ones found by Kull et al (2015), who showed that South-oriented windows could achieve a positive energy balance during the heating period. In these window cases, the solar heat gains overcompensated for the night-time heat losses. In line with the initial
hypothesis, as the window size increased to 30% of the floor area, it resulted in a higher heating demand. This is most likely because the additional solar heat gains were not necessary for achieving the minimum indoor temperature during the day; therefore, no heating energy was saved, while the night-time heat losses increased. The higher the window U-value, the larger the impact from increasing the window size. This explains why glazing type D resulted in a smaller variation in the heating demand when the window size was increased. In most cases, a large window (30% WFR) with glazing type D, resulted in an equal or lower heating demand compared to a small window (10% WFR) with all other glazing types. The effect of the combined U-value and window size is also apparent by the fact that the heating demand increases significantly with increased window size when the window angle is lower (higher U-value). Similarly, when the window g-value is lower, increasing the window size has a larger impact on the heating demand, just like when the U-value is higher. This is why increasing the window size in building cases with glazing type C resulted in a more significant increase in the heating demand, compared to the cases with other glazing types.

6.2 Heating power

This study showed that orientation has no influence on the peak heating loads, which is because the heating peak occurs during the night, when all orientations are more or less equal in terms of heat loss through the window. Shading also had a minimal effect on the results and this is most likely due to the low insulating quality of the shading device, which cannot significantly reduce night-time heat losses.

Glazing types A (U=1.10 W/m²K, g=0.64, T vis=0.81), B (U=1.00 W/m²K, g=0.51, T vis=0.75) and C (U=1.00 W/m²K, g=0.30, T vis=0.61) performed similarly in terms of peak heating loads. This indicates that the window U-value, and not the g-value, is the key property affecting the heating peak load, which is reasonable, since this peak occurs when there are no solar gains. This also explains why the building cases with glazing type D (U=0.50 W/m²K, g=0.50, T vis=0.65) have the lowest heating peaks.

6.3 Cooling demand

The cooling demand is only for the mechanical ventilation system, for adjusting the supply air temperature. There are no cooling units in the simulated room cases, as this is common practice in newly constructed residential buildings in the Nordic region. Therefore, the cooling demand does not vary much between the different building cases, as it mostly depends on the outdoor air temperature. However, as there is a heat exchanger in the air-handling unit, small differences between the cases can be observed, depending on the resulting room operative temperatures.

Similarly, negligible differences occur between the different glazing types. Shading also has a minimal effect on the resulting cooling demand of each case. As mentioned before, this is most likely because the cooling demand is mainly defined by the outdoor temperatures, which are the same for all building cases.
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The South, East and West-oriented cases perform quite similarly, while the North has a slightly lower cooling demand. This can be explained by the fact that the North-oriented windows yield less solar gains and thus result in lower room temperatures – which is also apparent from the resulting heating demands described earlier. The extracted air from the room is at a lower temperature, thus limiting the heat transfer to the inlet air in the heat exchanger. As mentioned in section 4.3.1.3, it is not possible to bypass the heat exchanger, so the room temperature always exchanges heat with the incoming air.

6.4 Cooling power

The cooling power results only refer to the cooling peak in the mechanical ventilation system, which supplies air at a constant temperature. As mentioned in section 4.3.1.3, there are no cooling units in the simulated rooms.

The cooling peak loads are in most cases only slightly reduced by the use of shading. The shading device blocks some solar heat gains, which would otherwise increase the indoor air temperature, which in turn transfers heat to the inlet air. In other words, the cooling peak remains lower when the room temperature is also lower. The building cases oriented towards the North are unaffected by the use of shading, and this is because on this orientation there are limited overheating hours when the shading would be activated. Additionally, the building cases with glazing type C (\( U=1.00 \text{ W/m}^2\text{K}, \ g=0.30, \ T_{\text{vis}}=0.61 \)) are less impacted by the use of shading, most likely due to the low g-value, which already prevents a large portion of solar heat from entering the building.

The North-oriented building cases generally have lower cooling peaks. This is because the solar heat gains, which would normally occur during peak cooling hours, are much less on the North, therefore the indoor temperatures remain lower. Since the indoor air exchanges heat with the incoming air before it is cooled, the cooling power required is lower.

When the WFR is 10\%, the cases with glazing type C have the lowest cooling peaks. This is due to the low g-value of this glazing type, which blocks a large portion of solar heat gains. However, when the WFR is 30\%, all glazing types perform similarly. It appears as if the solar heat gains are significant enough in all cases to cause the same cooling peaks.

The building cases with windows did prove to have higher cooling peaks than the windowless cases, but increasing the WFR from 10\% to 30\% did not increase the peak loads significantly more. The cooling peaks in all cases occur when the indoor temperature is higher than the outdoor, so due to the heat exchange between the extract and inlet air, the cooling peak loads should vary with window size, similarly to the indoor temperature. Therefore, these results are difficult to explain. It seems as if the inlet air bypasses the heat exchanger during the cooling season when the indoor air is warmer than the outdoor, which is not how the ventilation system was designed, see section 4.3.1.3.
6.5 Electricity demand for lighting

This study shows that all glazing types resulted in a similar electricity demand for lighting, despite the fact that they have different levels of visual transmittance (from 0.61 to 0.81). Most likely this is because when daylight was sufficient, even the glazing types with the lowest visual transmittance let through sufficient daylight to achieve an indoor illuminance of 300 lux and keep the electric lighting off. This also explains why the electricity demand is not reduced significantly more when the WFR increases from 10% to 30%, which is in line with the results found by Du et al (2014).

The West-oriented window cases resulted in the lowest overall electricity demand for lighting. This was expected, since the lighting is needed in the afternoon and evening when the occupants are home, and the orientation with the most natural light during this time is the West. The second lowest results were from the South-oriented window cases, because during the occupied times, after the West, the most natural light occurs when the window is facing South. Additionally, the South-facing window receives more daylight in general, over the course of the whole day, affecting the lighting demand even during the morning occupied hours. This again emphasizes the need for properly orienting residential rooms in order to save both heating and lighting energy.

As expected, the use of shading proved to increase the lighting demand negligibly. This is due to a number of factors. Firstly, the overheating hours, when the shading is activated, are not many in most building cases. Secondly, many of the hours when a minimum light level of 300 lux is required are during times when there is no daylight. Finally, even when the shading is activated, which would most likely coincide with high solar radiation peaks and thus high outdoor illuminance levels, it still allows some light through (a total of 10%-14% depending on the glazing type), which is sufficient in many cases to keep the electric lighting off. Similar results have been obtained by other researchers (Dubois & Flodberg, 2013).

6.6 Total energy demand

The total energy demand of the building cases is mainly determined by their heating demand, as they are located in a cold climate, and additionally have no active cooling system. Therefore, all resulting patterns are in line with those of the heating demand, described in section 6.1.

This study showed that orientation is a defining parameter in the total energy demand, mainly due to its effect on the heating demand. The South-oriented cases have the lowest energy demand, due to increased solar exposure, which reduces the heating demand. The second-lowest energy demand was achieved by the West-oriented cases, as they have solar heat gains during the later part of the day, thus reducing the night-time heating demand. The North-oriented cases have the highest overall energy demands, due to the lack of passive solar heat gains. Orientation also affects solar access, which is connected to the electric lighting demand, but these annual values were generally much lower than the heating demand. Du et al (2014)
also reached this conclusion. Finally, it must be noted that as expected, orientation has a smaller effect on the results as the window becomes more horizontal.

In addition, this study shows that glazing size plays an important role, and in most cases increasing the WFR from 10% to 30% brought forth a significant increase in the energy demand. The higher the glazing U-value, the larger the impact of glazing size on the energy demand. Similarly, the lower the glazing g-value, the higher the impact of glazing size on the results. This is why the results from glazing type C (U=1.00 W/m²K, g=0.30, Tvis=0.61), which has a very low g-value, were affected the most by the increase in window size, while the cases with glazing type D (U=0.50 W/m²K, g=0.50, Tvis=0.65), which has a very low U-value and an intermediate g-value, were affected the least by the increase in window size. This is in line with the findings of Persson (2006). In the same manner, the more the window is tilted towards the sky, which increases its U-value, the more the energy demand is affected by window size. Finally, for façade (90°) windows, when the window is facing South, window size is less important in terms of annual energy use.

The initial hypothesis that glazing construction is more important than orientation was confirmed. A well-performing glazing type will outperform a “weaker” one on all orientations.

In line with the findings of Kragh et al (2008), Panek et al (2010) and the Belgian Building Research Institute (2010), the ranking of the different glazing types remained the same on all building cases and window angles. Glazing type D (U=0.50 W/m²K, g=0.50, Tvis=0.65) proved to perform the best in all cases, indicating that very low U-values combined with moderate g-values are the optimal solution for cold climates, confirming the findings of Kull et al (2015). For the same reason, glazing type C (U=1.00 W/m²K, g=0.30, Tvis=0.61), which has a very low g-value, performed the worst. It is interesting that even a larger window (30% WFR) with glazing type D performs better than a smaller window (10% WFR) with glazing type C, on all orientations, showing that glazing construction is often more important than window size. Glazing type A (U=1.10 W/m²K, g=0.64, Tvis=0.81) slightly outperformed glazing type B (U=1.00 W/m²K, g=0.51, Tvis=0.75), due to its higher g-value. As expected, in a Nordic climate, solar heat gains are generally beneficial.

This study showed that in certain cases, a window is more energy-efficient than a wall (up to 13%), contrary to the findings of Persson et al (2006) and Du et al (2014). This was true for most South-oriented cases with smaller windows (10%). In the study carried out by Persson et al (2006), the simulated building was a Passive House, therefore more thermally resistant than the buildings studied in this project. This indicates that the building construction has a significant impact on the results. Apparently, in a Passive House, where heat losses are minimized, the potential energy savings from solar heat gains through a glazed surface do not compensate for the added heat losses during the night. In this study, where the exterior wall of the buildings had a U-value of 0.18 W/m²K, adding a window was sometimes more energy-efficient than having no window. The glazing type is of high importance here, because type C for example never managed to outperform the wall. Glazing type D on the other hand, performed better than the wall on all orientations when the WFR was 10% and also with a 30% WFR on the South. These results prove that a reasonably-sized window (10% WFR),
oriented towards the South, with a low U-value and a moderate g-value, allows enough passive solar heat gains into a building to overcompensate for night-time heat losses. Even if the window is larger (30% WFR) but on the South, in many cases it is possible to achieve the same energy demand as a hypothetical windowless version of the same building. This was true for glazing types A and B at a 90° angle. A 30% WFR with glazing type D on the South yielded a lower energy demand than the windowless case at both a 90° and 45° angle. Considering the other benefits of having a larger window (sunlight, view, connection to the outdoors), the energy balance of low U-value and moderate g-value glazing definitely validates the selection of a larger glazed area.

The use of shading had no significant impact on the results, which was expected since it barely affected the heating, cooling or lighting demands individually.

6.7 Overheating

The use of shading proved highly effective in reducing overheating hours to a minimum. However, when the window size was larger than 10% of the floor area, shading could not completely eliminate overheating. This is most likely due to the high outdoor temperatures, which result in conductive heat transfer through the glazing to the indoor space, and also the accumulation of heat before the shading is activated.

Contrary to the initial hypothesis that a West orientation would result in the highest indoor temperatures, it was mainly the South-oriented cases that had the most overheating, in terms of absolute temperatures and number of hours above 25°C. The only exception to this trend were the 90° windows with glazing types B (U=1.00 W/m²K, g=0.51, Tvis=0.75), C (U=1.00 W/m²K, g=0.30, Tvis=0.61) and D (U=0.50 W/m²K, g=0.50, Tvis=0.65) when the WFR was 10%. In these cases, the most overheating hours occurred when the window was oriented towards the West. These window cases have the lowest U-values, so a reasonable conclusion would be that a low U-value combined with a low g-value are more effective in reducing solar heat gains on the South than on the West. This confirms the conclusion reached by Kull et al (2015) that a window g-value has more impact on the South. At the same time, low window U-values keep the internal heat gains from escaping the building envelope. Since the internal heat gains occur in the late afternoon and evening, when the West side receives solar radiation at almost perpendicular incidence angles (when the window is vertical), it is expected that a West-oriented vertical window would result in more overheating than a South-oriented one if its U-value is low.

Another interesting result is that when shading is active, glazing type D (U=0.50 W/m²K, g=0.50, Tvis=0.65) results in less overheating hours than glazing type C (U=1.00 W/m²K, g=0.30, Tvis=0.61), despite the fact that the latter has a much lower g-value. This leads to the conclusion that when direct solar radiation is obstructed by a shading device, a lower glazing U-value results in less overheating by resisting conductive heat transfer from the warmer outdoor air to the indoor environment.
Orientation has a strong impact on the results, especially when the window has a 45° angle. This is because of the resulting solar incidence angles. The North-oriented building cases have the least overheating hours, especially when the window has a 90° angle. The South and West orientations yielded the worst results, as was expected.

It must be noted that in all cases, the number of hours when the indoor temperature is above 25°C is negligible. This is partially due to natural ventilation through the window opening, and the fact that the mechanical ventilation system constantly supplies air at 16°C into the room. In addition, the rooms have a relatively high infiltration rate (1-1.3 ac/h at 50 Pa), which causes additional heat loss. Finally, overheating in many cases refers to temperatures in the range of 25.5-26.5°C, which are usually considered very acceptable.

6.8 Daylight

In the building cases that did not have shading, the daylight levels were understandably only affected by the glazing $T_{vis}$. When shading was implemented, not all cases were affected similarly, because the shading was activated when the indoor temperature exceeded 24°C. Therefore, the shading was activated more often in the building cases with glazing type A ($U=1.10$ W/m²K, $g=0.64$, $T_{vis}=0.81$) than in those with type C ($U=1.00$ W/m²K, $g=0.30$, $T_{vis}=0.61$), because the latter has a much lower g-value and consequently less overheating.

The use of shading reduces the average illuminance levels mainly in the South-oriented cases. This is because a South-oriented window is exposed to the most direct solar radiation, so shading is activated during more hours and results in a significant change in the conditions. This also explains why the use of shading does not affect the North-oriented cases.

When comparing the trends between average and maximum daylight values, it is clear that in the North-oriented cases, the ratio of average to maximum daylight is much higher compared to the other orientations, which is understandable because daylight is more uniform and fluctuates less on the North, since there is never direct sunlight.

The glazing type seemed to affect the maximum illuminance more than the average values. This could be explained by the fact that a small difference in the percentage of $T_{vis}$ can result in a large difference in actual lux levels when the solar radiation is at its peak.

The maximum illuminance recorded over the course of a year was negligibly affected by the use of shading. This is due to the fact that shading is only activated when the indoor temperature exceeds 24°C and in certain occasions during the year there is intense solar light without overheating.

An interesting result was that the West-oriented cases appeared to receive more light than the East. This could possibly be related to the specific climatic conditions that were simulated in this study. Sunny weather possibly occurs more often in the afternoon, which would affect the West side.
Orientation and shading seemed to be of less importance when the window was tilted 15°. This is because the solar incidence angle on the window is more similar for all orientations and because there are less overheating hours when the shading is activated.
7 Conclusions

The main conclusions from this study are summarized as follows:

- In a heating-dominated climate, where solar heat gains are vital to the energy balance of a building, South-oriented windows perform the best.

- Orientation is significant in determining the energy performance of a building when the windows have a 90° (vertical) or 45° angle, but is of less importance when the window angle is 15°.

- The optimal glazing type for a residential building in the Nordic climate is one that allows high solar heat gains, while reducing heat losses to a minimum. In other words, a glazing type with a moderate g-value (0.50-0.64) and a very low U-value (0.5 W/m²K) will have the best energy performance. Glazing types with very low g-values perform poorly in this climate, where solar heat gains are necessary.

- A reasonably-sized window (10% WFR), when oriented towards the South to maximize solar heat gains, can result in a positive energy balance. Increasing the window size to a WFR of 30% will impact the energy balance negatively, as the additional solar heat gains cannot compensate for the night-time heat losses, unless the window has a very low U-value (0.5 W/m²K).

- A window with a very low U-value (0.5 W/m²K) and a moderately low g-value (0.50) can minimize the impact of increasing the window size in terms of annual energy use. In other words, a well-insulated window allows more flexibility in the selection of window size. During the design phase of a building, if a larger window size is preferred, then very heat-resistant glazing is the only energy-efficient solution, but for smaller windows, a moderately heat-resistant glazing type could suffice.

- A higher glazing g-value also allows more flexibility in the selection of window size. This also means that a window with a very low g-value (0.30) will have a significantly lower performance as window size increases, due to a relatively larger increase in heat losses compared to passive solar gains.

- The peak heating load is unaffected by orientation, as it occurs during night-time heat loss, and is mainly defined by the window U-value.

- With the implementation of lighting controls, windows understandably reduce the electricity demand for lighting. However, this energy reduction is not significant compared to the effect windows have on a building’s heating demand.

- Window ranking based on energy performance remains the same regardless of window angle and orientation. The most energy-efficient window at 90° on the South, for example, will outperform the other window types on all angles and orientations.
• The use of shading can significantly reduce overheating hours, although this is not a significant issue in Nordic climates.

• The glazing g-value and shading have the highest impact on reducing solar heat gains when the window is oriented towards the South, where the total direct solar radiation is the highest.

• In the absence of direct solar radiation, low window U-values reduce overheating during the warm season, as they resist conductive heat transfer from the ambient outdoor air to the indoor space.
8 References


9 Appendix

Table 5. Simulation results for 90°-window geometries.

<table>
<thead>
<tr>
<th>Window inclination</th>
<th>Orientation</th>
<th>WFR</th>
<th>Glazing type</th>
<th>Shading</th>
<th>Heating Demand</th>
<th>Heating Peak</th>
<th>Cooling Demand</th>
<th>Cooling Peak</th>
<th>Electricity Demand for Lighting</th>
<th>Total Energy Demand</th>
<th>Average illuminance</th>
<th>Maximum illuminance</th>
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<td>38.3</td>
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<td>17.5</td>
<td>8.8</td>
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<td>8.1</td>
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Table 6. Simulation results for 45°-window geometries.
The energy balance of windows
M. N. Maragkou

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Appendix
### Table 7. Simulation results for 15°-window geometries.

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The energy balance of windows
M. N. Maragkou

Appendix
The energy balance of windows
M. N. Maragkou

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