Assessing the European Daylight Standard: A Simulation-Based Study of Daylight, Energy, and Thermal Loads in Swedish Residential Buildings

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Master thesis in Energy-efficient and Environmental Buildings
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Lund University

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

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Abstract

Standards play a significant role in shaping our environment and everyday life. In the context of the built environment, they ensure consistency of quality between different projects. The European Daylight Standard EN17037 "Daylight in buildings" is one of those standards, currently in use in the European Union, and was established to secure enough natural light indoors to achieve spaces that are both bright enough and offer occupants views of the outdoor environment. However, it has been established that it is excessively ambitious and lacking in variability and adaptability regarding the diverse daylight conditions that are encountered in Europe.

The aim of this master thesis is to examine the mismatch between the European Daylight Standard's recommendations and the reality of the built environment in Sweden's largest cities. Initially, an extensive background regarding daylighting history and practices, as well as recent energy policies in Europe is provided to set the theoretical framework of the thesis. Then, daylight provision, energy consumption and indoor thermal comfort are simulated for 28 different buildings, located in Stockholm, Gothenburg and Örebro. Compliance rates with the European Daylight Standard are determined, as well as energy classification per building and overheating in indoor spaces during the summer. Then, five buildings, representative of different typologies, and least compliant with the European Daylight Standard, are selected and their openings are enlarged to provide more light. The impact of this measure on daylight, energy consumption and indoor overheating is simulated again and reexamined. Finally, daylighting, energy and overheating behavior trends in different typologies and urban contexts are discussed, and conclusions and general suggestions for the standard are made.

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List of abbreviations

ACC – ACC Glass and Façade

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

BBR – Boverkets Byggregler (Swedish Building Regulations)

BRE – British Building Research Establishment

BREEAM – Building Research Establishment Environmental Assessment Method

CAV – Constant Air Volume

CBDM – Climate-Based Daylight Modelling

CIE – Commission Internationale de l'Éclairage (International Commission on Illumination)

D – Daylight Factor

DHW – Domestic Hot Water

EN – European Norm

EP_{pet} – Primärenergital (Primary Energy Number)

ET – Target Illuminance

ETM – Minimum Target Illuminance

EU – European Union

EUI – Energy Use Intensity

FAR – Floor Area Ratio

FEBY – Forum för Energieffektivt Byggande (Swedish Passive House Standard)

g-value – Total Solar Energy Transmittance

HSB – Hyresgästernas Sparkasse- och Byggnadsförening (Tenants' Savings and Building Association)

MAPE – Mean Absolute Percentage Error

MEPS – Minimum Energy Performance Standards

NZEB – Nearly Zero-Energy Building

PBL – Plan- och Bygglagen (Planning and Building Act)

sDA – Spatial Daylight Autonomy

T_{vis} – Visible Light Transmittance

U-value – Thermal Transmittance

VDF – Vertical Daylight Factor

WFR – Window-to-Floor Ratio

1 Introduction

Daylighting has always been a major concern in the design of buildings. At the same time, measures required for optimization of daylight are often in conflict with those for energy conservation. These contrasting needs have shaped building design throughout the centuries; at times the visual comfort and aesthetics that daylight promises have taken center stage, while in other cases design trends promoted focus on thermal comfort or the safety of inhabitants, often at the cost of daylight provision. Humans' efforts to control both daylight and the energy use of their buildings have been ongoing from the dawn of our species and have led to numerous examples of ambitious feats of architecture and engineering. (Phillips, 2004)

These concerns have become the topic of recent focus, especially with current concerns about the impact of the indoor environment on human health and well-being, (Yousef Al horr, Arif, Katafygiotou, & Mazroei, 2016), the need for limiting building energy use for the phasing out of fossil fuels, and the general trends towards greener constructions and building operation. In recent years, research efforts have focused on both daylight provision and building energy; this decades-spanning effort has led to several standards and legislative frameworks. Among those, the European Daylight Standard EN 17037 "Daylight in Buildings," (from now on referred to as the European Daylight Standard) was the first standard covering expressly daylighting requirements in buildings. The standard, which was first published in 2018, was established to secure enough daylight indoors to achieve spaces that are both bright enough and offer occupants quality views towards the outdoor environment (Svenska Institutet för Standarder; European Committee for Standardization, 2021).

The standard, which covers four aspects of daylight quality – daylight provision, sunlight access, view out, and glare -, has been often found to be somewhat too demanding in terms of daylight provision, lacking in variability and adaptability regarding the diverse daylight conditions that are encountered throughout the European continent. This has led to low compliance rates in terms of daylight provision among the existing building stock in many European countries (Sepúlveda, De Luca, Thalfeldt, & Kurnitski, 2020), as well as for potential new buildings in newer developments (Czachura, Kanters, Wall, & Gentile, 2024).

The ambitious daylight requirements encourage the use of larger window areas to meet minimum illuminance levels. However, bigger windows mean increased heat losses in winter and additional solar gains in summer, which can increase energy use and overheating risks. As a result, improving daylight performance is likely to come at the cost of poorer energy performance. This may create a conflict between daylight optimization and energy efficiency goals.

1.1 Objective

The aim of this master thesis is to examine the relationship between the European Daylight Standard's criteria and the implications for energy use in the existing residential building stock in Sweden. For the analysis, twenty-eight buildings representative of the Swedish residential building stock were selected, with the case study buildings located in Stockholm, Gothenburg and Örebro.

1.2 Research questions

This thesis attempts to answer the following question, limited in scope to the Swedish residential building stock:

- How does compliance with the Daylight Standard affect the energy use and thermal comfort in residential buildings?

The thesis also explores whether it is possible to increase the compliance rate of the current building stock with the European Daylight Standard by providing larger vertical openings.

As a secondary question, the compliance rate of the current building stock in Sweden with the European Daylight Standard is examined, thus expanding upon the research article "Proposal for revised criteria for daylight provision in the European daylight standard based on calculations for Swedish multifamily residential buildings" (Jin, et al., 2025), upon which this study it is based.

2 Background

2.1 Recent history of daylighting in buildings

Daylight has governed the lives of people ever since prehistoric times. As technology advanced, man started to shape architecture and urban planning around it, controlling access to it and how it penetrates interior spaces (Phillips, 2004).

In the 20th century, several developments regarding daylighting and lighting can be noted. The industrial advancements of the previous centuries paved the way for modernism's love for glass and transparency, with iconic architects such as Ludwig Mies van der Rohe and Louis Isadore Kahn using these innovations to their fullest potential and experimenting with opacity, transparency and translucency. (Stathaki, 2025) On the other hand, the increasing availability of electrical lighting and cheap fossil fuels led increasingly to the rapid construction of buildings that relied almost solely on mechanical systems and artificial lighting for the regulation of their indoor environment. (Dubois, 2025)

The problematic aspects of this approach were revealed during the energy crisis, as well as with the rise of ailments such as Sick Building Syndrome. Daylighting was brought to the forefront of the discussion again as a cheap, readily available and healthy way to light buildings. (Phillips, 2004)

2.2 The European Daylight Standard

Measures to determine the performance of a space when it comes to daylight provision have been developed ever since the end of the 19th century. Specifically, the Daylight Factor (D), which is the ratio between the indoor and outdoor illuminance under an overcast sky, is said to originate at the end of the 19th century, as a result of the research of Alexander Pelham Trotter. The theory and procedure for the definition of D was developed further and refined in subsequent years, parallel to the advancement of technology that enabled more accurate illuminance measurements. The specific illuminance pattern that constitutes a standard overcast sky was further defined by the CIE

(International Commission on Illumination / Commission Internationale de l'Eclairage) in 1955 as one that follows a specific equation. This type of sky is, since then, the only one considered valid for the calculation of D. (Mardaljevic & Christoffersen, 2013)

After the energy crisis of the 70s, the need for reducing energy use brought to the forefront the discussion for the underutilized advantages of daylight. The possibility of providing well-lit spaces while limiting reliance on expensive electric lighting, as well as the emergence of new findings on the health benefits of natural light, resulted in efforts being made to improve daylight provision in buildings (Mardaljevic & Christoffersen, 2013). At that time, D was often used as a measure for determining whether a room is adequately daylit. However, with the advent of computer simulations in the 90s, the possibility to simulate the daylighting of a space under different sky conditions emerged. This became the basis of Climate Based Daylight Modelling (CBDM), which is the practice of simulating and predicting the daylight provision in a space by using 3D modeling software and standardized meteorological files for the specific location of the building, usually over the course of a year. While D is still widely used, CBDM is becoming increasingly popular, and has been successfully utilized in numerous architectural projects. Its main advantage over D is the ability to consider differing weather and climate conditions that prevail in various locations, thus giving a more complete understanding of the quality and quantity of daylight in a space. (Mardaljevic, Christoffersen, & Raynham, 2013)

CBDM and D-based criteria were subsequently adopted by several national legislations (such as the criteria approved by the US Illuminating Engineering Society in 2012) and voluntary certification systems, such as the Building Research Establishment Environmental Assessment Method (BREEAM), developed by British Building Research Establishment (BRE). (Mardaljevic, Christoffersen, & Raynham, 2013)

The European Daylight Standard was first published in 2018. It presents designers with four types of assessment of daylight in interiors: daylight provision, view out, exposure to sunlight and protection from glare. Daylight provision may be quantified using both D and CBDM. As far as CBDM goes, an illuminance method closely resembling the dynamic daylight metric Spatial Daylight Autonomy (sDA) is utilized. This metric sDA is defined as the percentage of a spatial plane that meets a minimum level of horizontal daylight illuminance for a fraction of a defined period (Dubois, Gentile, Laike, Bournas, & Alenius, 2019). For the European Daylight Standard, the specified spatial plane for one room is located 0,85 m above the floor, and it is formed by offsetting the edges of the room inwards by 0,5 m. The period is 50% of the daylight hours of the location of the building. There are three levels of compliance: minimum, medium and high. The required percentages and illuminance levels for side-lit spaces for each level of compliance are detailed in Table 13 in the Appendix.

For compliance using D, the standard provides tables where the minimum average D required to reach a certain level of illuminance is provided by country. The illuminance levels referenced are 100 lx, 300 lx, 500 lx and 750 lx (Svenska Institutet för Standarder; European Committee for Standardization, 2021).

2.3 The applicability of the European Daylight Standard – a literature review

A literature review is conducted in order to assess the state of the art regarding the perception of the European Daylight Standard by the academic and architectural community. Several searches are made in the sites scopus.com and sciencedirect.com, using the terms "European Daylight Standard," "Daylight in Buildings," and "EN 17037." An initial selection of 32 papers relevant to the topic is thoroughly examined, and 9 of them are chosen, as they strictly refer to applying the standard to different contexts and testing compliance levels.

Across several research papers, a mismatch between the requirements of EN 17037 and preceding national standards is noted, as well as different compliance levels for the standard's distinct evaluation methods. Bournas (2020) conducted simulations across 10888 rooms in 54 buildings located in Stockholm and Örebro to control compliance with different daylight criteria. All buildings are found to present low compliance rates with the European Daylight Standard. Specifically, only 21% of rooms complied with the D-based criterion. A disagreement between the CBDM and D-based criteria is also noted, in the form of 22% - 37% differences in compliance between the two. This disagreement between the two criteria is also reported by Koster, Rafiee, & Brembilla (2025), who simulated the daylight performance of two standard buildings when located into three distinct urban contexts in the Netherlands, with low, medium and high urban densities. D targets are found to be significantly more difficult to reach than illuminance (CBDM-based) ones. This paper also notes a correlation between urban density and differences between daylight availability on the bottom versus the top floors of buildings, and highlights the importance of taking urban surroundings into account when simulating daylight performance, as their absence can lead to an overestimation of compliance of up to 85%.

De Luca & Sepúlveda (2021) simulate a room in 1728 combinations of size, glazing area, urban environment and orientation in order to examine compliance with different aspects of the European Daylight Standard. In total, 21,7% of these combinations fulfill the D-based daylight provision criterion of the standard, compared with 64,8% fulfilling the Estonian standard's demands for residential buildings, and 48,8% fulfilling its demands for office buildings. Compliance rates for the D-based daylight provision criterion vary also by urban density: combinations set in a low-density environment are 17,9% compliant, in a medium-density environment are 14,4% compliant, and in a high-density environment are 3,6% compliant. Paule & Flourentzou (2019) conduct a similar experiment where they simulate the daylight access of a room oriented to the south in four different climates: Athens, Lausanne, Berlin and Oslo. The room's dimensions, window-to-floor ratio (WFR), glazing type, and outdoor obstruction angle are kept the same throughout all simulations. Shading is implemented through a system of outdoor horizontal slats, their inclination depending on solar altitudes. Examining compliance with the illuminance-based criterion of the European Daylight Standard, it is found that medium and high levels of compliance are easily reached in southern locations with a sunny climate like Athens, but require increasing the WFR to reach in locations like Berlin or Oslo. This increase in turn leads to increased heating energy needs. Jin, et al. (2025) simulate 30 Swedish buildings for compliance with several daylight provision criteria, and finds a 16% compliance with the European Daylight Standard's D-based criterion, and a 32% compliance with its illuminance-based criterion.

Gougouli Dimitriadou & Khin (2023) examine the compliance of 6 residential buildings in Thessaloniki, Greece, to the demands of the European Daylight Standard. 78% of the rooms are found to not meet the minimum level of the D-based criterion. Compliance rates for the illuminance-based criterion are higher, and one building even achieves 100% compliance to its minimum level, but none of the 6 achieve compliance to any higher levels than minimum.

Šprah & Košir (2019) analyze the relationship between Vertical Daylight Factor (VDF) values on the facades of residential buildings in Slovenia and the interior D values, while controlling compliance with the EN 17037 D-based criterion. Their findings suggest that even lightly shaded facades lead to significant drops in compliance. According to their results, deep rooms require low Floor Area Ratios (FAR) to remain compliant, from 0,93 to 0,5 depending on site coverage.

Inconsistences have been reported regarding the standard's view out evaluation criteria as well. Waczynska, Sokol, & Martyniuk-Peczek (2021) compared the computational evaluation of view out with the qualitative evaluation based on occupant observations in classrooms in Gdansk, Poland. Statistically significant differences are recorded between quantitative and qualitative evaluations, as the students that participated in the experiment consistently rated the view quality as one level lower than that suggested by the standard. This is then corroborated by Sepúlveda, De Luca, Varjas, & Kurnitski (2022), who ran a similar study comparing standard evaluation of view out in office rooms in Estonia with qualitative evaluation from office workers that occupied these spaces. Even here the participants report lower view quality than that suggested by the standard.

2.4 The Swedish context regarding daylighting

According to the general recommendations of the Swedish BBR (Boverkets byggregler), or building regulations authored by Boverket, the Swedish National Board of Housing, Building and Planning, a government entity dealing with development and planning issues and regulations. (Boverket, 2024), "rooms or separable parts of rooms where people stay more than occasionally shall be designed and oriented in such a way that good access to direct daylight is possible, unless this is unreasonable taking into account the intended use of the room." (Boverket, 2022) This is often translated in practice as the daylight factor of a room being at least 1%. A minimum window-to-floor ratio (WFR) of 10% is also recommended.

BBR also calls for at least one window to be installed in areas occupied more often than occasionally, the view through which would allow the following of the variations of the seasons and the time of day. Thus, a ceiling window is not allowed to be the only source of natural light in these types of spaces. (Boverket, 2022)

2.5 The European and Swedish contexts regarding building energy use

In Europe, the European Union has been shaping the policies of member states regarding climate action and the energy performance of buildings. Sweden is no exception; national Swedish strategies regarding must comply with the EU's directives (European Commission, 2024).

There are two main EU directives that deal with these subjects: Directive (EU) 2024/1275 on the energy performance of buildings and Directive (EU) 2023/1791 on energy efficiency. These documents establish measures to enhance energy efficiency and reduce greenhouse gas emissions in all member states. (European Commission, 2024)

Directive (EU) 2024/1275 emphasizes the need for member states to develop comprehensive renovation strategies for the decarbonization of national building stocks by 2050. Details of how this can be achieved are expressed in its different articles, the most important of which are the following. Article 2a promotes the establishment of long-term renovation strategies in order to encourage deep renovations of buildings that are cost-effective and bring about results. Article 7 stresses the need for minimum energy performance requirements for new buildings, which should achieve nearly zero-energy building (NZEB) status, and the construction of zero-emission buildings from 2030 onwards. Finally, Article 9 requires member states to set minimum energy performance standards (MEPS) for the renovation of existing buildings (European Parliament; Council of the European Union, 2024).

Directive (EU) 2023/1791 introduces the Energy Efficiency First principle in Article 3, obligating member states to prioritize energy efficiency in their policies and investments. Article 5 sets forth energy savings obligations, requiring annual reductions in energy use (European Parliament; Council of the European Union, 2023).

Sweden has responded to these demands from the EU's directives in several ways. One of the most important ones is Sweden's Third National Strategy for Energy Efficient Renovation. The document outlines the condition and renovation needs of Sweden's building stock, focusing on energy consumption for different purposes and corresponding greenhouse gas emissions. Furthermore, it presents strategies for improving energy efficiency in buildings, such as the “Rekorderlig Renovering” and “Halvera Mera” methods, the first one aiding property owners to identify cost-effective energy efficiency measures during renovations, and the second having reducing energy use in buildings by half as its main target. The document discusses financing options for renovations, such as green loans, and other monetary incentives, such as increases in rent, and even presents specific renovation scenarios developed by Chalmers Industriteknik. These separate renovations into 4 categories, depending on how extensive they are, and predict their effect on building energy consumption based on computer simulations. Finally, the country’s goals related to energy efficiency are described, such as achieving 100% renewable electricity by 2040, and observations regarding the present efforts to reach these goals are laid out. (Swedish Ministry of Infrastructure, 2019)

In practice, this information, as well as other documents, determines the demands that Sweden’s Plan- och Bygglagen (PBL) sets on both new construction and renovations. PBL is Sweden’s building code, where both mandatory measures and recommendations for buildings are presented. (Landsbygds- och infrastrukturdepartementet, 2010) This is then clarified by BBR. (Boverket, 2018),

For all types of buildings in Sweden, their energy use is defined by their primary energy number (Primärenergital, EP_{pet}) which is a summation of the normalized values of the energy use of the building for different purposes, corrected by a geographic factor, multiplied by a weighting factor dependent on the energy carrier (such as district heating, electricity, heat pumps, etc.) and divided by the total area that is being heated, expressed in kWh/m^2/year. It is calculated by the following formula:

$$EP_{pet} = \frac{\sum_{i=1}^{6}\left(\frac{E_{uppv,i}}{F_{geo}} + E_{kyl,i} + E_{tvv,i} + E_{f,i}\right) \times VF_i}{A_{temp}} \quad (1)$$

Where $E_{ppv,i}$ is the yearly heating energy, $E_{kyl,i}$ is the yearly cooling energy, $E_{tvv,i}$ is the yearly energy spent on the generation of domestic hot water (DHW) and $E_{f,i}$ is the premise energy, that is to say energy related to the needs of the building, when the apparatus is located inside, underneath or attached to the outside of the building. It includes fixed lighting in shared areas, electricity for elevators, pumps, fans, motors, control and monitoring equipment, etc. A_{temp} is the total heated area of the building. F_{geo} is an adjustment factor dependent on the location of the building. (Boverket, 2024) The relevant values to this project are presented in Table 18 in the Appendix.

Finally, VF_i is a weighting factor depending on the carrier of the energy (Boverket, 2024). The factor values are presented in Table 19 in the Appendix.

Depending on building type, BBR sets limits on the maximum acceptable EP_{pet}. For multifamily houses, the limit is currently 75 kWh/m^2/year (Boverket, 2024). This is applicable to newly constructed buildings (Boverket, 2022).

When it comes to older buildings, EP_{pet} is used for assigning an energy class to the building, as per the protocol of the European Union Energy Label (European Commission, 2024). The classification is done according to the values presented in Table 1. $EP_{pet,nyprod}$ refers to the highest acceptable EP_{pet} value for a newly produced building of the type being examined.

Table 1 Calculation of energy class for existing buildings according to EP_{pet} values. (Sveby, 2024)

Energy Class	**Ep_{pet} Value**
A	$EP_{pet} \leq 0{,}50 * EP_{pet,\ nyprod}$
B	$0{,}50 * EP_{pet,\ nyprod} < EP_{pet} \leq 0{,}75 * EP_{pet,nyprod}$
C	$0{,}75 * EP_{pet,\ nyprod} < EP_{pet} \leq 1{,}0 * EP_{pet,nyprod}$

D	$1,0\ \mathrm{EP}_{\mathrm{pet,\ nyprod}} < \mathrm{EP}_{\mathrm{pet}} \leq 1,35*\ \mathrm{EP}_{\mathrm{pet,nyprod}}$
E	$1,35*\ \mathrm{EP}_{\mathrm{pet,\ nyprod}} < \mathrm{EP}_{\mathrm{pet}} \leq 1,8*\ \mathrm{EP}_{\mathrm{pet,nyprod}}$
F	$1,8*\ \mathrm{EP}_{\mathrm{pet,\ nyprod}} < \mathrm{EP}_{\mathrm{pet}} \leq 2,35*\ \mathrm{EP}_{\mathrm{pet,nyprod}}$
G	$2,35*\ \mathrm{EP}_{\mathrm{pet,\ nyprod}} < \mathrm{EP}_{\mathrm{pet}}$

2.6 Swedish multi-family housing typologies

The building categorization is based on work of Jin et.al. (2025), as the 28 buildings presented here are part of the same dataset. The buildings can be assigned to five categories, according to their form:

- Large courtyard blocks (Stenstadskvarter and Storgårdskvarter), buildings with few floors surrounding a courtyard.
- Low-rise multi-apartments building (Lamellhus), battery-formed low-rise constructions, most often constructed in mid-20th century in the suburbs.
- Point tower (Punkthus), taller, tower-like buildings with circulation often in the middle of the floor plan.
- Semi-closed courtyard blocks (Lamellhus halvslutna gårdar), detached units built around courtyards in the suburbs.
- High-rise multi-apartment building (Skivhus), rectangular detached constructions of 8-9 stories on average.
- Postmodern blocks (Postmoderna reformkvarter), a freer style mimicking old urban construction. (Jin, et al., 2025)

Aside from this categorization, the construction periods and methods of each building are of foremost importance, especially due to the impact they have on energy efficiency. Based on the work of Björk, Kallstenius, & Reppen (2013), the buildings are separated into an additional 15 categories, depending on construction period, materials and methods. These archetypes are presented in detail in Appendix B – Detailed construction typologies. A short summary is also provided in Table 2.

Table 2 A short summary of the construction typologies of Swedish multi-family housing used in this project.

Construction Typology	**Description**
County governor houses, younger	Stone ground floor, wooden upper, 1880–1940, simple windows, varied forms
Brick houses, national romanticism	Brick walls, concrete slabs, decorative entries, 1910s–20s, small-paned windows
Thick houses, brick	Deep (14–16 m), brick/concrete mix, central corridors, 1920–40s, dark interiors
Thin houses, brick	Shallow (≈8 m), better daylight, parallel brick volumes, 1930s
Low-rise, aerated concrete	Gas concrete blocks, 3 floors, balconies, 1940s–60s, courtyard planning
Low-rise, modular	Prefabricated sandwich concrete panels, triple glazing, 1960s–80s
Tower, 3 floors, aerated concrete	Compact 3–5 floors, one stairwell, 1940–60s, gas concrete
Tower, 6 floors, brick	Brick-clad concrete, 6–8 floors, post-elevator adoption, 1930s–40s
Tower, lightweight concrete	6+ floors, poured concrete, lightweight blocks, 1950s–60s, experimental
High-rise, lightweight concrete	8–9 floors, Miljonprogrammet, park setting, prefab lightweight blocks
High-rise, modular façade elements	Prefab room-sized façades, in-situ slabs/walls, Miljonprogrammet, 1970s
High-rise, modular	Full prefab concrete system, synthetic insulation, 1970s–80s
Barge house, lightweight concrete	Late 1970s, aesthetic focus, reused elements, dense city centers
Courtyard blocks, concrete frame	1980s, postmodern, reinforced concrete, varied façades, increased insulation
Low-rise, concrete frame	1980s–2000s, concrete/steel structure, layered façade walls, wall systems

3 Methodology

In order to answer the research questions, daylight and energy simulations are performed on a database of 28 3D models of buildings located in Stockholm, Gothenburg and Örebro (Jin, et al., 2025; Rogers, Dubois, Tillberg, & Östbring, 2018), as shown in Table 4.

First, the number and percentage of rooms in the models that fulfill the requirements of the European Daylight Standard is determined, using the sDA and D criteria. Next, energy models of the buildings are created, and the energy use of the buildings is simulated. Overheating hours (April to September) are also checked. Finally, five of the worst performing buildings in terms of daylight are selected, each of them representing a distinct form typology, and the windows are scaled up. Two simulations are carried out, one where the same pane assembly is kept, and one where it is replaced with a 3-pane low-e assembly. Data regarding daylight, energy and overheating of these five buildings is recorded, in order to take note of the impact that efforts to improve daylight performance would have on energy and thermal comfort. The process is presented in detail on Figure 1.

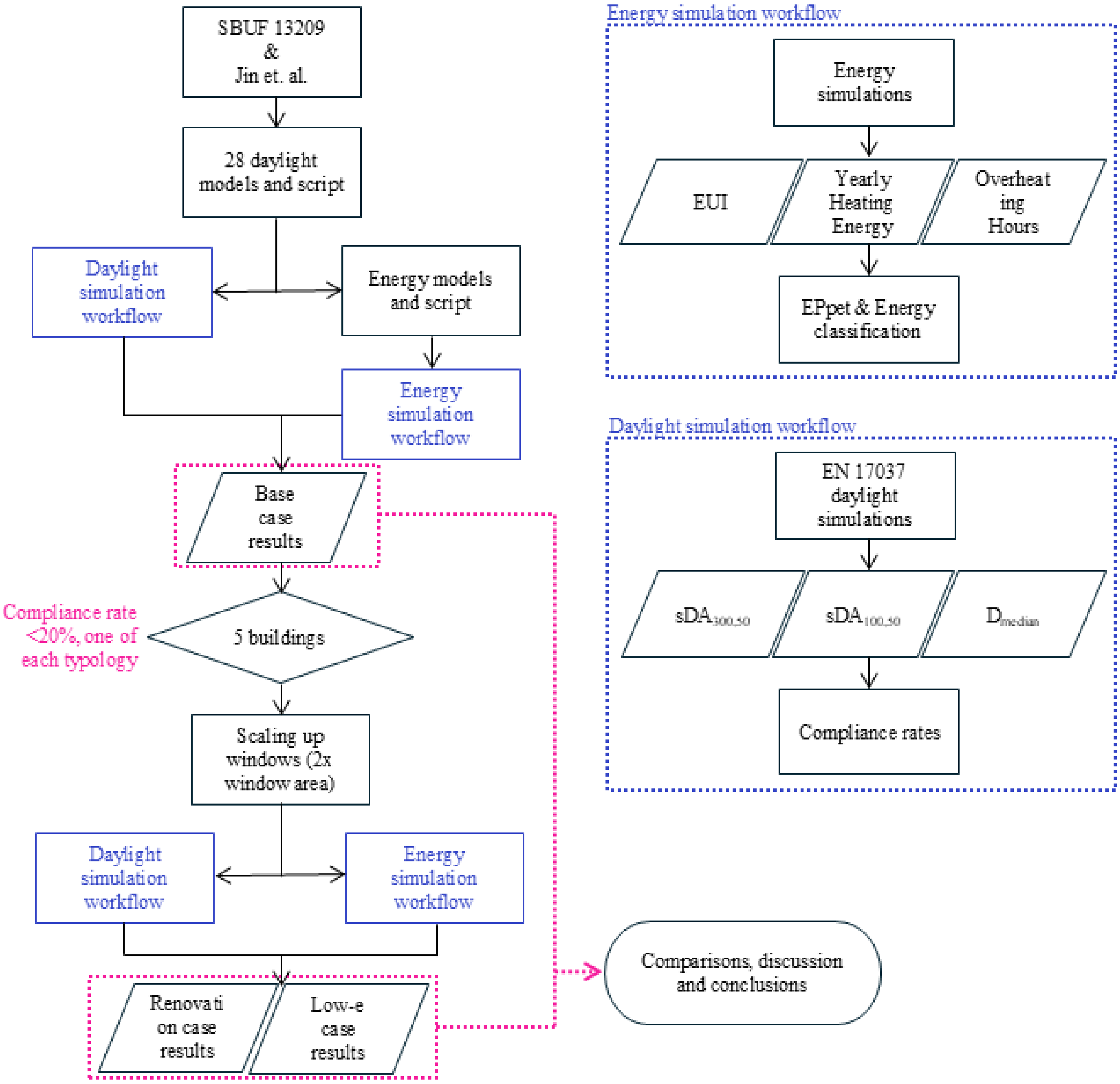


Figure 1 Chart showing the project's workflow.

3.1 Study variables

This study involves several distinct variables, which are categorized into independent, dependent and confounding in order to properly evaluate the results of the experiment (Creswell & Creswell, 2018) and the impact of environmental factors on the daylight, energy and overheating performance on the buildings.

The independent variables of this project are window size and glazing assembly. In the renovation case, only window size is altered. However, both window size and glazing assembly are changed from the base case to the low-e case. When comparing between the renovation case and the low-e case, the window size remains unaltered, but the glazing assembly is changed.

The dependent variables are daylight access, energy performance and overheating during the summer. These are primarily measured through sDA and D values for daylight (Svenska Institutet för Standarder; European Committee for Standardization, 2021), EP_{pet} values and energy classification for energy performance (Boverket, 2022), and percentage of the hours of the period from April to September when the operative temperature of an energy zone exceeds 26°C, for overheating. This is based on recommendations from the Swedish Public Health Agency for healthy indoor environments during heat waves in the summer (Folkhälsomyndigheten, 2023).

Numerous confounding variables can be identified in this experiment. They can be divided into two main categories: those related to the building's geometry, and those related to the urban context.

The building geometry category includes characteristics such as building height, room depth, and window placement, and especially window head height, as it directly affects lighting distribution in a space (Tregenza & Wilson, 2011). Wall thickness also tends to vary between buildings, and affects daylight access. Construction methods, details and materials affect energy use, as well as the airtightness of the buildings, measured by their infiltration rate. The overheating of the buildings is affected by the same variables (Fanger, 1970).

The urban context category includes variables such as the urban density of the area each building is in, the average height of the surrounding buildings, and the height of the tallest building. Those have implications for the shading patterns being projected on the examined building, and thus its daylight access (Compagnon, 2004).

The variables are summarized in Table 3. It is worth noting that this is not an exhaustive list, as daylighting, energy use and overheating are complicated phenomena, influenced by numerous interacting variables (Littlefair, King, Howlett, Ticleanu, & Longfield, 2022; Ratti, Baker, & Steemers, 2005).

Table 3 A summary of all the variables present in the project.

Variable type	**Category**	**Variables**
Independent	Geometry	Window size
	Construction	Glazing assembly
Dependent	Daylight access	$sDA_{100,50}$ $sDA_{300,50}$ D
	Energy performance	EP_{pet} Energy class Yearly heating energy

	Overheating	Overheating hours Solar gains
Confounding	Building geometry	Building height Room depth Window head height Wall thickness Room orientation Construction sets Inflitration rate
	Urban context	Urban density Heights of surrounding buildings Height variation of surrounding buildings

3.2 Software utilized

The 3D modeling program utilized is McNeel's Rhinoceros 7. For daylight and energy simulations the parametric design software Grasshopper is used, specifically its plugins Honeybee and Ladybug. These free and open-source plugins offer a way to interface with the programs EnergyPlus and Radiance, which are the basis of the energy and daylight simulations respectively. The choice of these pieces of software is motivated by their integration within architectural workflows, flexibility in parametric modeling, and extensive user community.

Radiance has long been considered a benchmark tool for daylight simulations due to its physics-based ray tracing algorithm, and its results have been validated against empirical measurements in numerous studies (Mardaljevic J. , 2000; Reinhart & Andersen, 2006). Similarly, EnergyPlus is a widely used simulation engine for energy modeling, developed by the U.S. Department of Energy, and has undergone extensive validation against ASHRAE Standard 140 and empirical datasets (Crawley, Hand, Kummert, & Griffith, 2001; U.S. Department of Energy, 2025). The Honeybee and Ladybug plugins have been shown to reliably interface with these engines and reproduce comparable results to standalone simulations, supporting their use in academic and professional contexts (Roudsari, Pak, & Smith, 2013)

3.3 Building selection

A sample of 28 existing Swedish residential buildings are selected. These had previously been a part of other industrial and academic research projects (Jin, et al., 2025; Rogers, Dubois, Tillberg, & Östbring, 2018), and it is assured that the selection is fairly representative of the Swedish building stock. The 3D models of these buildings, which had already been adapted for daylight simulations, were provided. Based on these, as well as initial permit drawings, the corresponding energy models are then created.

The buildings are located in Stockholm, Gothenburg, and Örebro. They were constructed between 1870 and 2010s. Due to the many changes in building technology during these years, as well as the rich aesthetic variation of the different styles that became prevalent in the last century, these buildings vary wildly in construction, appearance, floorplan arrangement and design philosophy. In addition to that, they are set in distinct kinds of urban context environments, from dense central city neighborhoods to suburban sprawl constructed during Sweden's Million Houses Program (Miljonprogram). The details of the buildings are presented in Table 4.

Table 4 The buildings used for the project simulations.

Id	Year	City	Address	Cadastral Reference	Floors	Rooms	Apartments

1	1987	Gothenburg	Erik Dahlbergsgatan 12	Vasastaden 64:13	4	42	18
2	1923	Gothenburg	Mariagatan 25	Kungsladugård 18:6	3	37	21
3	1928	Gothenburg	Terrassgatan 3	Johanneberg 2:6	6	70	16
4	1935	Stockholm	Tranebergsvägen 36	Mösseberg 9	4	24	10
5	1936	Stockholm	Stagneliusvägen 51	Soldatgossen 1	7	136	41
6	1938	Stockholm	Glimmerbacken 8-10	Dynamiten 2	4	45	14
7	1937	Stockholm	Hallebergsvägen 34-36	Holaveden 3	4	45	14
8	1938	Stockholm	Margretelundsvägen 36-38	Tändhatten 1	4	39	14
9	1938	Stockholm	Tranebergsvägen 10	Kärnröret 2	4	41	10
10	1943	Stockholm	Rålambsvägen 21	Signallyktan 1	7	144	37
11	1960	Gothenburg	Tamburingatan 9	Rud 8:10	10	200	42
12	1936	Stockholm	Stagneliusvägen 35	Stjärnsången 1	7	119	48
13	1946	Stockholm	Ymsenvägen 9	Fegen 1	8	92	25
14	1934	Stockholm	Wollmar Yxkullsgatan 53	Postiljonen 15	6	110	42
15	1935	Stockholm	Disponentgatan 1	Luxlampan 6	7	201	85
16	1875	Stockholm	Åsögatan 168	Pahl 8	7	75	32
17	1910	Stockholm	SanktEriksgatan 13	Karlsvik 42	6	85	29
18	1963	Stockholm	Stora Sällskapetsväg 28-30	GulaKnapparna2:16	9	261	68
19	1962	Stockholm	Ålgrytebacken 10	Vårfrugillet 1	4	128	36
20	1968	Stockholm	Risingeplan 12-24	Drakensberg 14	9	174	46
21	1965	Stockholm	Ekholmsvägen 345-363	Harholmen 1:8	7	129	48
22	1965	Stockholm	Brantholmsgränd 40-72	Branthomen 1:2	7	173	44
23	1983	Stockholm	Svartviksslingan 73-79	Minneberg 4	6	140	44
24	1982	Stockholm	Horisontvägen 31-39	Flygplanet 1	5	229	68
25	1981	Stockholm	Pilotgatan 42	Gondolen 1	5	173	59
26	1983	Stockholm	Varmfrontsgatan 2-74	Carmfronten 1:21-22	6	203	48
27	1950	Stockholm	Wergelandsgatan 26	Skärkarlen 9	4	173	56
28	1952	Orebro	Hjalmar Bergmansväg 54	Baronbackarna B:5	10	126	54

The buildings’ form and construction typologies are presented in Table 14, Table 15, Table 16 and Table 17 in the Appendix.

3.4 Constructing the base case

3.4.1 Daylighting simulations setup

The daylight models are simulated using a Grasshopper script modified over the original one developed by Jin & Chen (2023).

The 3D models are designed to enable simulation of daylight in relevant rooms of each building. For a room to qualify, it has to be a living space that is regularly occupied (such as a living room, bedroom, kitchen, etc.). Rooms that do not receive daylight or house an auxiliary function (such as bathrooms or circulation spaces) are not modeled and thus disregarded. Windows are modeled with a standardized profile with a frame thickness of five cm. Outside wall thickness ranges from 30 to 60 cm, and interior wall thickness is 15 cm. Surrounding buildings are drawn as volumes with minor detailing. Illustrations of one of the daylight models, including a closeup to one of the windows and a section view, are presented in Figure 2.

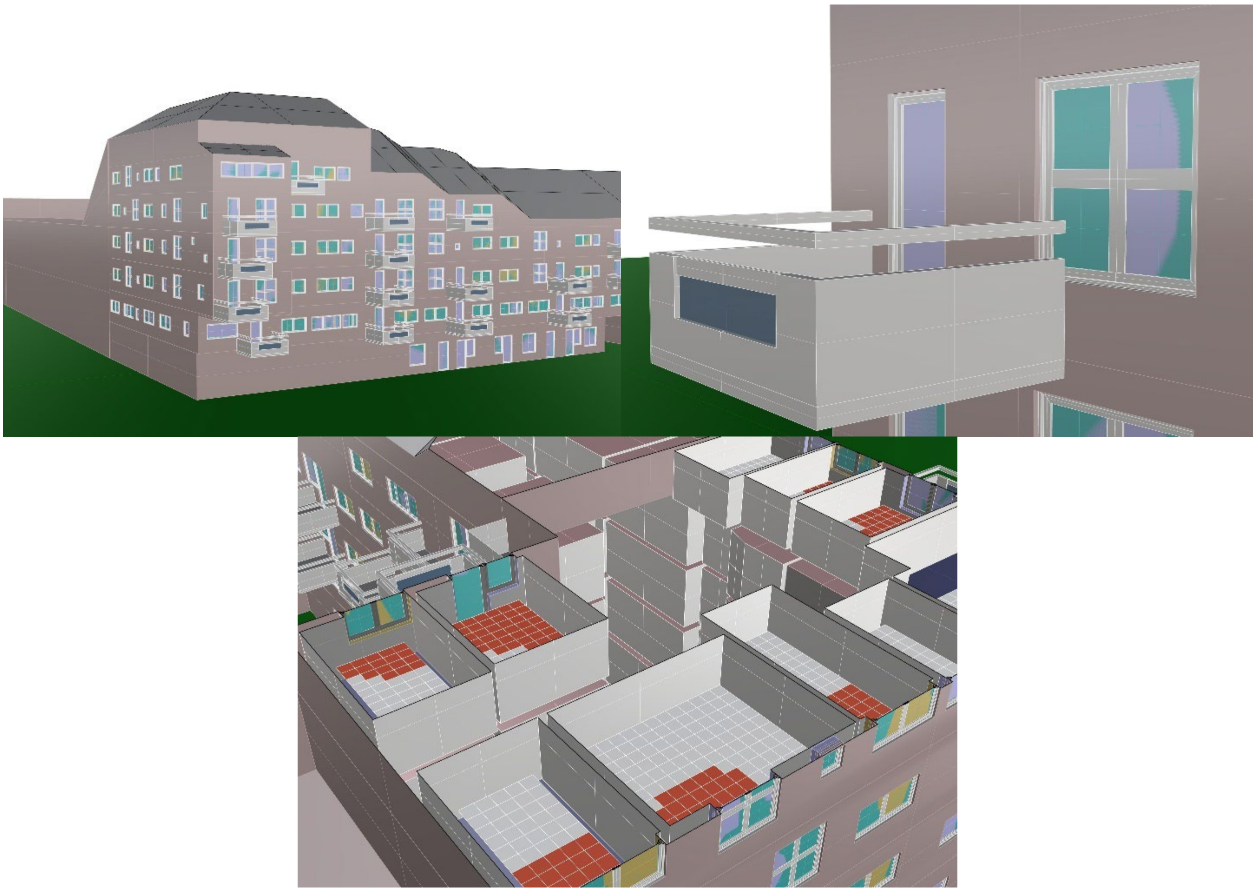


Figure 2 An illustration of one of the daylight models used in the project. Upper left: overall view, upper right: focus on windows, bottom: section view, showing only residential rooms adjacent to the façade are modeled and simulated.

Radiance is used for daylight simulations, accessed through Honeybee. The reflectance and transmittance values used are specified in Table 5. The values used are a combination of average values as suggested by the European Daylight Standard, as well as values specified in the 3D model files themselves:

Table 5 Reflectance, specular and transmittance values used in the Radiance simulation of the models

Building Element	**Transmittance**
Window glass	0,7
Interior glass	0,87
Building Element	**Reflectance**
Balcony glass	0,3
Floor	0,3
Interior wall	0,7
Interior ceiling	0,8
Window profile	0,8

Window sill and niche	0,7
Outer wall	0,3
Surrounding buildings	0,2
Balcony floor	0,3
Balcony profile	0,2
Balcony underside of slab	0,7
Ground	0,2

Two types of simulations are run for the selection of buildings. The first one is a compliance test for the minimum requirements of the European Daylight Standard Illuminance Criterion using sDA. The requirements are presented in detail in section 2.2 of the present paper. The second one was a D simulation, using CIE standard overcast sky. Both simulations are conducted on a grid plane 0,85 m above floor level. The grid size is 0,3 m, in accordance with common practice in daylight simulation to balance result resolution and computational efficiency. A finer grid provides more detailed spatial information, but significantly increases simulation time without proportionally improving accuracy in most cases. A grid spacing of 0,3 m is therefore widely considered a suitable compromise for room-scale daylight assessments (Reinhart & Walkenhorst, 2001). A 0,5 m wide band from the walls inwards is excluded from the simulation, as suggested by the European Daylight Standard (Svenska Institutet för Standarder; European Committee for Standardization, 2021). The sDA$_{100,50}$, sDA$_{300,50}$ and D values for each room are recorded.

For sDA simulations, the Radiance parameters presented in Table 6 are utilized:

Table 6 Radiance parameters for the sDA simulations

-ab	**-ad**	**-as**	**-c**	**-dc**	**-dp**	**-dr**	**-ds**	**-dt**	**-lr**	**-lw**	**-ss**	**-st**
6	25 000	4096	1	0,75	512	3	0,05	0,15	8	4,00E-07	1	0,15

For D simulations, the Radiance parameters presented in Table 7 are used instead:

Table 7 Radiance parameters for the D simulations

-aa	**-ab**	**-ad**	**-ar**	**-as**	**-dc**	**-dj**	**-dp**	**-dr**	**-ds**	**-dt**	**-lr**	**-lw**	**-ss**	**-st**
0,1	6	4096	128	4096	0,75	1	512	3	0,05	0,15	8	0,005	1	0,15

3.4.2 Energy simulations setup

While the initial daylight models focused on testing the daylight performance in a room-by-room basis, the energy models that are derived from them separate the building into energy zones that correspond with their separation into apartments and circulation zones. This is done to simplify the simulations and reduce simulation time.

The circulation zones are not separated by floor as the apartments are, being instead a singular volume spanning all relevant floors. This is done to reflect the interconnection of the floors through stairwells. For the buildings that share walls with neighboring buildings, these walls are modeled as adiabatic. This is achieved through modeling an adiabatic energy zone that borders the relevant wall, thus achieving this boundary condition. Finally, the surroundings are modeled as simple volumes, spanning a radius of about 200 m around the building that is examined. This serves the purpose of simulating solar gains and the shading of the building's energy zones. Two representative examples of the energy models can be seen in Figure 3.

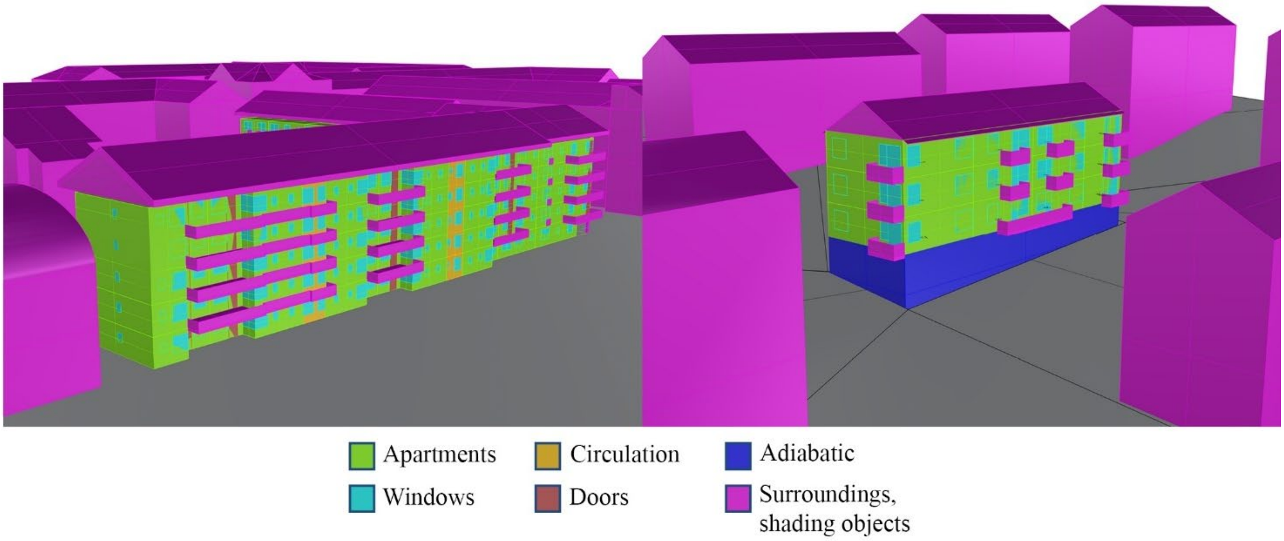


Figure 3 Two examples of 3D energy models, with a clarification of the color coding of zones and objects.

Based on the construction typologies presented in 2.6, fifteen construction sets are developed. Each building, based on their construction year, floor plan arrangement, and façade details, are assigned a corresponding construction set. The U-values of each construction element are presented in Table 20 in the Appendix.

As far as windows are concerned, although there is the possibility that these buildings could have different window assemblies installed, a simple two-pane clear glass window, with 6 mm thick clear glass panes and a 6 mm air gap in-between, with a U-value of 3,11 W/m^{2}K and a visible light transmittance value (T_{vis}) of 0,7 is utilized for all base case simulations. This is partially due to lack of data when it comes to the actual construction details of the buildings, but also to eliminate factors other than the geometry and size of the openings, which is the focus of this project, from influencing the simulation results. This is also the average U-value calculated for the windows in European buildings according to research. (TNO Built Environment and Geosciences, 2011)

The g-value of the base case windows is 0,75. This value was chosen due to it being close to the average g-value measured by other research projects for these types of fenestration systems (Li & Wu, 2025).

When it comes to internal loads, the following values derived from bibliography (Kasolas, 2020; Kronvall & Boman, 1993) are used, presented in Table 8.

Table 8 The internal load values used in energy simulations.

Zone	**Lighting / W/m^2**	**Equipment / W/m^2**	**Occupancy / People/m^2**	**Temperature Setpoint / °C**	**Infiltration / m^3/s**	**Ventilation / m^3/s**
Apartment	0,53	3,42	0,02	21	0,0006 - 0,0003	0,00035
Circulation	0,36	0	0	21	0,0006 - 0,0003	0,00035

As DHW does not affect the interior environmental conditions or heating energy consumption, and is unrelated to daylight, it is excluded from the simulation.

When it comes to schedules, equipment and ventilation are assumed to be always on, as that is a common condition in Swedish multi-family housing. Lighting and occupancy are set to vary according to the schedule in Figure 4 on weekdays. Occupancy variation on weekends follows the schedule on Figure 5, as it is assumed that, due it not being a working day, some people may choose to not leave the house. The lighting schedule on weekends is unchanged from Figure 4. This is due to the assumption that lighting will most likely be turned off during the day, even if the space is still occupied.

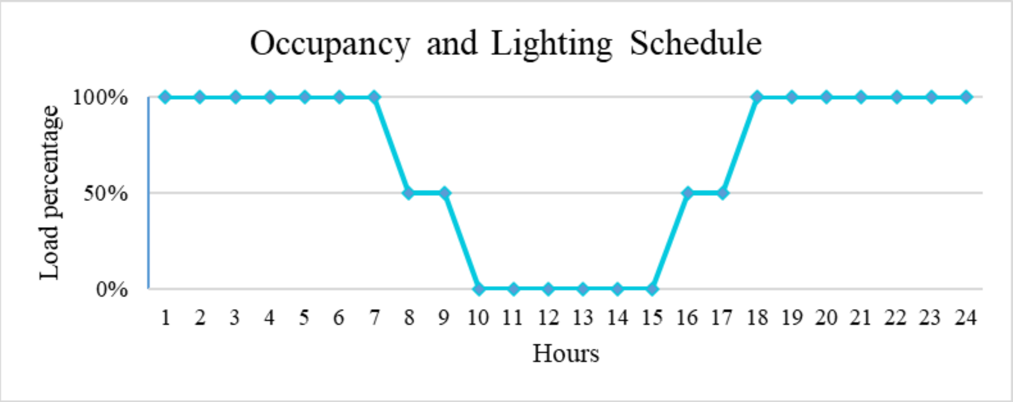


Figure 4 Load percentage of lighting and occupancy by hour during weekdays.

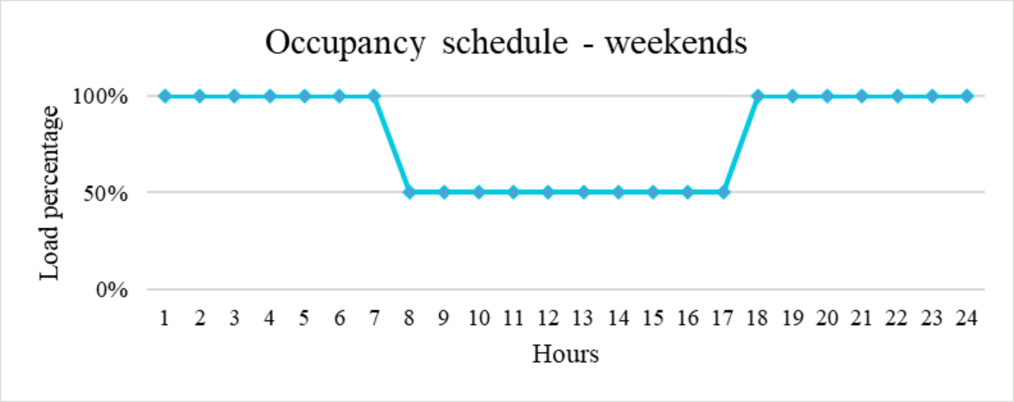


Figure 5 Load percentage of occupancy by hour during weekends.

Shading devices such as blinds are not included in the simulation due to them not being often used in Sweden, but also due to the unpredictability of their schedules when used. Cooling is not included in the simulations either, as this is also extremely uncommon in Sweden, especially in residential buildings.

The output of the energy simulations are: 1) the Energy Use Intensity (EUI), 2) the overheating hours of each energy zone from September to April, and 3) the annual heating energy for each zone.

Subsequently, the sum of the annual heating energy for each building is calculated and used to calculate the EP_{pet} of each building. The heated area of each building is recalculated taking into account the extra area of the intermediate floors of the circulation zones. The E_{tvv} and E_f are assumed to be 25 kWh/m^2 and 15 kWh/m^2 respectively, based on preexisting research (Sveby, 2009). It is once more assumed that no cooling is present, and, because all buildings are located within larger cities or in their suburbs, the carrier for heating and DHW is assumed to be district heating, and electricity for premise energy.

3.5 Constructing the daylight renovation case

After the base case simulations are carried out, the buildings are compared with regards to their compliance with the European Daylight Standard. Specifically, the focus of the comparison is on the illuminance criteria. The percentage of rooms that do and do not comply with the standard are calculated for each building, and five buildings, one of each form typology, as mentioned in section 2.6, are chosen that have a room compliance rate of under 20%. These buildings are then the focus of the next phase of the project, where potential "renovation cases" are tested. The windows are scaled up, and performance is once more simulated, for both energy and daylight, once for the same assembly as in the base case (this case is henceforth referred to as "renovation case"), and once for a triple-glazed assembly with low-e coating on the outermost pane (henceforth referred to as "low-e case").

The buildings that were selected for 'renovation' and further simulations are presented in Table 9.

Table 9 The buildings selected for the renovation and low-e cases.

Id	Typology	Year	City	Address	Cadastral Reference	Floors	Rooms	Apartments
1	Postmodern blocks 'Postmoderna reformkvarter'	1987	Gothenburg	Erik Dahlbergsgatan 12	Vasastaden 64:13	4	42	18
10	Point tower 'Punkthus'	1943	Stockholm	Rålambsvägen 21	Signallyktan 1	7	144	37
14	Multi-apartments building 'Lamellhuskvarter'	1934	Stockholm	Wollmar Yxkullsgatan 53	Postiljonen 15	6	110	42
16	Large courtyard block ('Storgårdskvarter')	1875	Stockholm	Åsögatan 168	Pahl 8	7	75	38
22	High-rise multi-apartment buildings 'Skivhusgrupper'	1965	Stockholm	Brantholmsgränd 40-72	Branthomen 1:2	7	173	44

3.5.1 Daylighting simulations setup

The strategy that is followed when scaling up the windows was to double their area. This is most often achieved by doubling their length. In cases where that was not possible, their height was also adjusted.

The total window areas of each building in the base and renovation / low-e cases are presented in Table 10.

Table 10 The total window area for base and renovation / low-e cases.

Building ID	1	10	14	16	22
Window Area Base Case / m^2	117	360	349	251	591
Window Area Renovation / Low-E Case / m^2	203	617	538	411	959

Additionally, the new layouts of the building facades are presented in Figure 15, Figure 16, Figure 17, Figure 18, and Figure 19 in the Appendix, compared side by side with the base case façade layouts. The same simulation settings as the base case are used, see section 3.4.1.

The T_{vis} remains at 0,7 for the renovations case but is reduced to 0,65 for the low-e case, as the triple glazing and low-e coating would reduce transmissivity.

3.5.2 Energy simulations setup

For the renovation case, the same inputs as the base case are used. For the low-e case, the window assembly simulated is comprised of a 6 mm thick glass pane with a low-e coating on the outside part of the window, followed by a 13 mm gap filled with argon gas, and two interior clear glass panes with a thickness of 6 mm, and a 6 mm air gap between them. The U-value of this assembly is 1,15 W/m^{2}K, and the g-value is 0,39. A comparison between it and the base case assembly is illustrated in Figure 6.

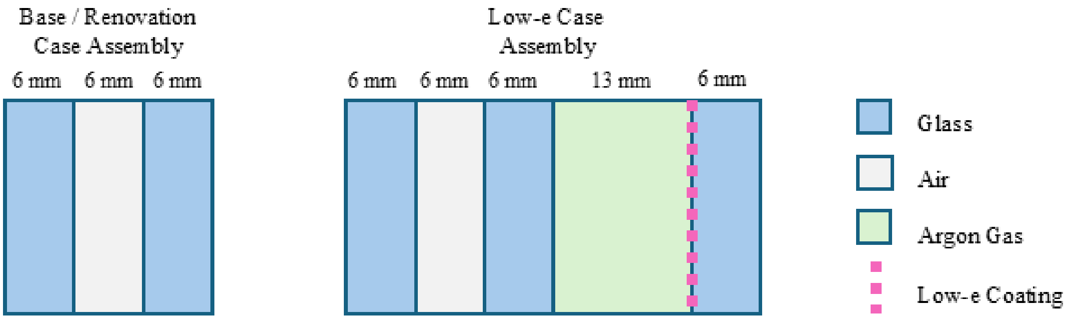


Figure 6 A comparison of the sections of the base / renovation case glazing assembly and the low-e case glazing assembly.

3.6 Statistical analysis of base case daylight results

To investigate the potential relationship between compliance levels to the European Daylight Standard, and the confounding variables mentioned in section 3.1, a statistical correlation analysis is conducted. The variables focused on in the analysis are urban density, expressed in m^3/m^2 built, average room depth, and WFR. These are calculated for each building and compared against the percentage of rooms in the same building that are compliant with the European Daylight Standard's illuminance criterion at the minimum level.

Two types of correlation tests are performed to capture both linear and monotonic relationships: the Pearson correlation coefficient is used to assess the strength of linear associations (Field, 2018), while the Spearman rank correlation coefficient is used to detect monotonic trends regardless of linearity (Mukaka, 2012). For each test, the corresponding p-value is calculated to determine the statistical significance of the observed relationships. (Hinkle, Wiersma, & Jurs, 2003)

The statistical analysis is done in Python using the pandas (NumFOCUS, Inc. , 2025) and scipy.stats (The SciPy community, 2025) libraries (McKinney, 2022).

3.7 Verification of base case primary energy numbers

To assess the plausibility of the primary energy numbers calculated through building performance simulations, a verification process is conducted to compare these numbers against publicly available official energy declarations. Energy declarations in Sweden are standardized and regulated by Boverket, offering a reliable source for verification purposes (Boverket, 2025).

The declared primary energy numbers reflect real world measured or estimated data based on utility bills and standardized use assumptions.

For each building, the percentual deviation between the simulated primary energy use (E_{sim}) and the declared primary energy use (E_{decl}) was calculated using the following formula:

$$Deviation\ (\%) = \frac{E_{sim} - E_{decl}}{E_{sim}} \times 100\ (2)$$

Additionally, the Mean Absolute Percentage Error (MAPE) was used as an aggregate indicator of overall deviation between simulated and declared values across the dataset. MAPE is defined as:

$$MAPE = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{E_{sim,i} - E_{decl,i}}{E_{decl,i}} \right| \times 100\ \ (3)$$

where n is the number of buildings analyzed. MAPE is a commonly used statistical measure in building energy modeling and is considered a robust indicator of model accuracy in verification processes. (Coakley, Raftery, & Keane, 2014; Fumo, 2014)

The purpose of this verification is to assess whether the simulated energy results fall within the acceptable range of deviation and support the validity of the modeling approach. This is because energy simulations inherently carry uncertainties due to unavoidable assumptions. (Raftery, Keane, & Costa, 2011)

3.8 Limitations

In the Swedish context, access to detailed data regarding construction methods and energy consumption data for individual buildings is limited. Instead, constructions are assumed based on archetypes derived by building's year of completion, typology and relevant bibliographic information. Furthermore, energy use is simulated based on generic input values and schedules for heating, lighting and equipment.

The specific details of the heating systems of each of the buildings are unknown. Therefore, for energy simulations, a basic Constant Air Volume (CAV) ventilation system combined with an ideal heater component. Had specific details about the exact systems used been available, more accurate results could be achieved. Please note that many of residential buildings located in cities in Sweden are served by district heating (Werner, 2017; Hayati, Akander, & Eriksson, 2022). There is generally no cooling in Swedish residential buildings.

The input values and schedules used to simulate equipment and lighting annual energy use, as well as occupancy, are based on previous research and assumptions. It should be noted however, that occupancy patterns in residential buildings are difficult to predict (Kanthila, Abhinandana, Beddiar, & Amirat, 2021)

4 Results

4.1 Base case results

A summary of the results of the base case simulations for both daylight and energy are presented in Table 21 in the Appendix.

4.1.1 Daylighting simulation results, comparison with European Daylight Standard benchmarks

When it comes to daylight simulation results, the conclusions drawn corroborate those of Jin, et al., 2025. Out of a total of 3414 rooms simulated, 48,4% (1654 rooms) comply with the minimum target illuminance ETM for the fraction of space (95% of the testing plane) specified by the minimum recommendation level European Daylight Standard, while 27,7% (945 rooms) comply with the target illuminance ET for the fraction of space (50% of the testing plane) specified by the minimum recommendation level European Daylight Standard.

In total, 27,5% of the simulated rooms are in compliance with the minimum requirements of the European Daylight Standard. This is in line with the results achieved by Jin et. al., 2025, who calculated a compliance rate of about 32%. The difference of 4,5% can be attributed to different weather files being used for the simulations.

The distribution of rooms according to typology, as well as the number of rooms meeting the specific criteria of the European Daylight Standard are presented in Table 11.

Table 11 Room distribution according to typology and European Daylight Standard compliance.

Typology	**Total Rooms**	**ETM Compliant**	**ET Compliant**
Large courtyard block ‘Storgårdskvarter’	267	64	18
Multi-apartments building ‘Lamellhuskvarter’	719	393	205
Point tower ‘Punkthus’	477	247	159
Semi-closed courtyard ‘Lamellhus halvslutna gårdar’	173	158	111
High-rise multi-apartment buildings ‘Skivhusgrupper’	991	441	224
Postmodern blocks ‘Postmoderna reformkvarter’	787	351	228
Total all	3414	1654	945

A bar chart of the percentage of rooms in each building that are compliant with the minimum requirement of the European Daylight Standard’s Illuminance Criterion is shown in Figure 7. The urban density and WFR of each building are also noted in the figure. That is to say, these rooms comply with both ET and ETM. A breakdown of the values mentioned in Table 11 as percentages is presented in Figure 8.

The lowest compliance rates are observed in large courtyard blocks. This can be explained due to the fact that this typology is often found in densely built urban areas, which leads to few solar gains because of shading from surrounding construction. Low compliance is also observed in some high-rise multi-apartment buildings. This may be due to their height, as well as that they are often located within expansive suburbian areas, among other high-rise construction. Thus, while higher floors may be well-lit, the lower ones are shaded for long periods of time, especially if one considers the low solar altitudes that are encountered in Sweden during the winter months.

The highest compliance rates are encountered in towers and semi-closed courtyards. The sample of semi-closed courtyards in this project is made up of just one building, and therefore general conclusions cannot be safely drawn for this typology. However, when it comes to towers, it can safely assumed that both their form and common surrounding construction explain their higher rates of compliance. They are thinner and taller than other typologies, and often surrounded by other sparsely built towers. Therefore, they do not encounter the shading issues and patterns of other typologies and urban environments.

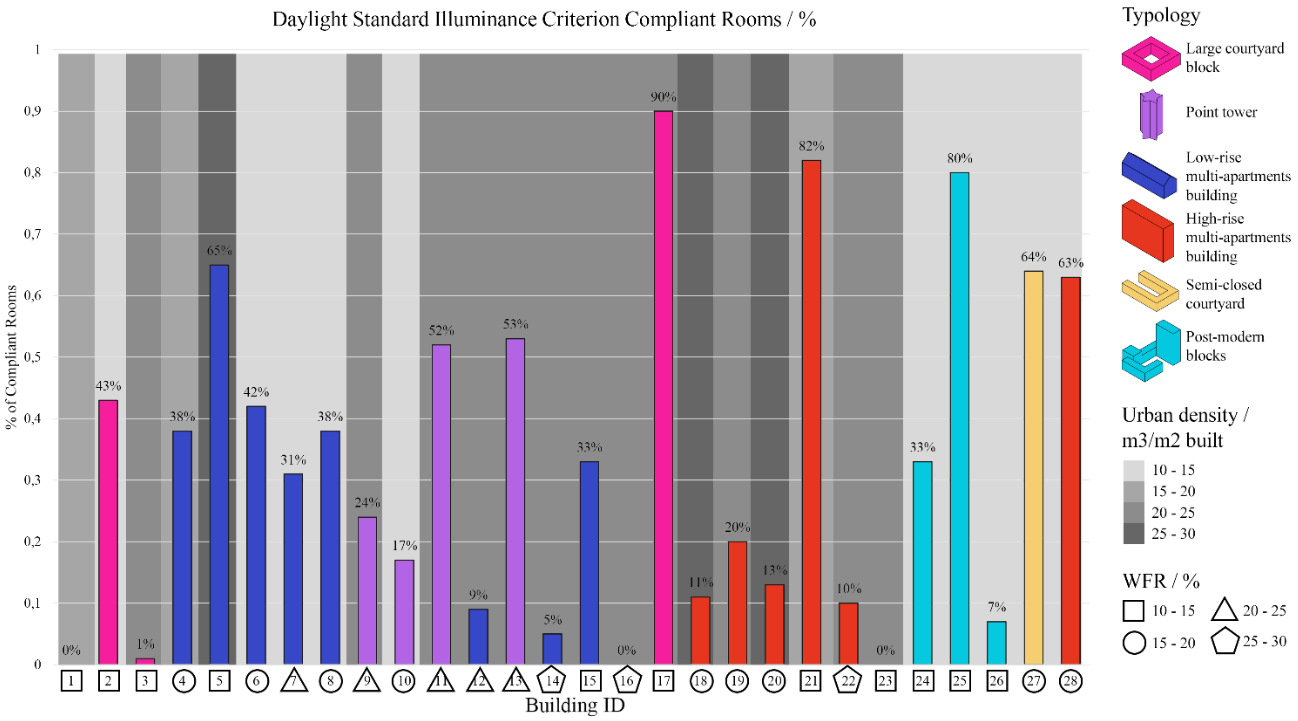


Figure 7 The percentage of rooms in each building which comply with the European Daylight Standard Illuminance Criterion.

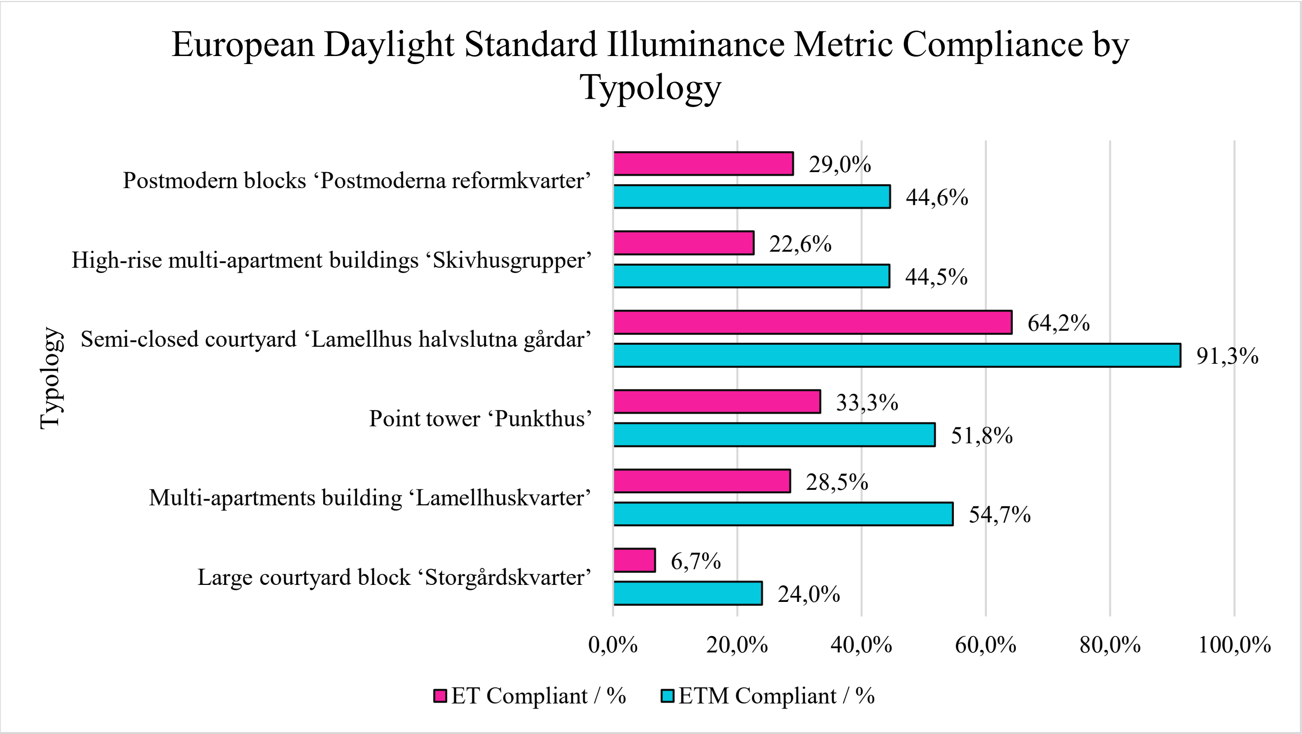


Figure 8 European Daylight Standard compliance percentages by typology.

The distribution of compliance percentages for each typology is presented in the box plot in Figure 9. It can be observed that high-rises and postmodern blocks present a large variation in daylighting behavior, while point towers and multi-apartment buildings behave more consistently.

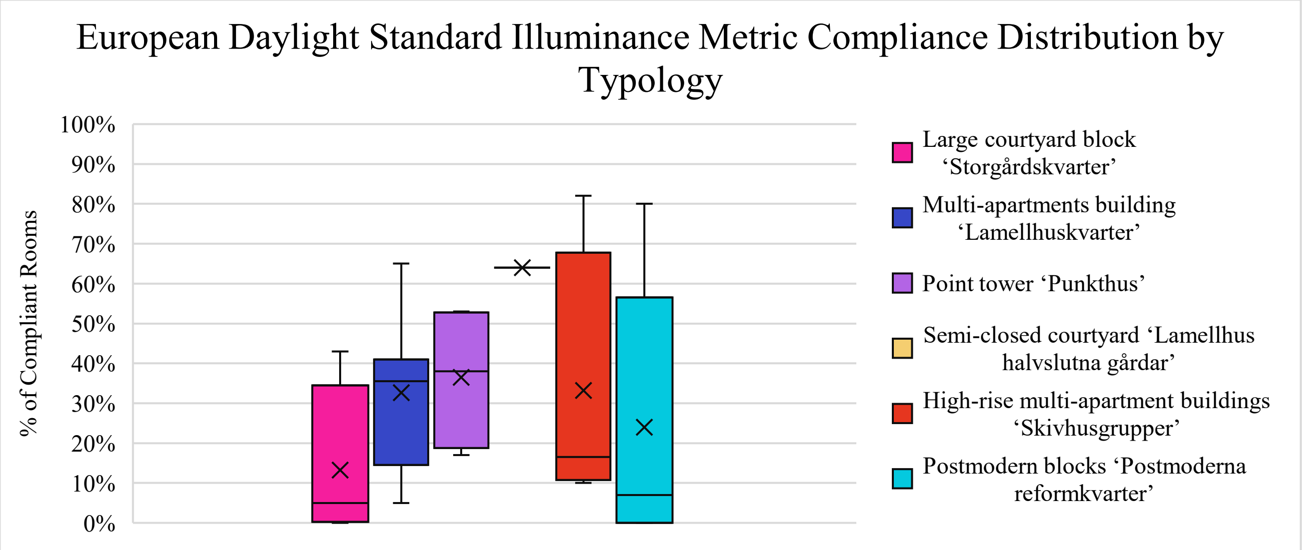


Figure 9 A box plot of the compliance percentages of each typology.

4.1.2 Daylight factor

Accounting for D leads generally to different levels of compliance. Of all the D values simulated, 65,36% are compliant with $D_{median}>0,8$, which is required to reach illuminance levels over 100lx, and 26,26% are compliant with $D_{median}>2,5$, which is required to reach illuminance levels over 300lx. A bar chart of compliance levels by typology is presented in Figure 10.

The D metric is generally not considered to be as reliable as a CBDM-based process. Thus, the thorough analysis of these results is outside the scope of this project.

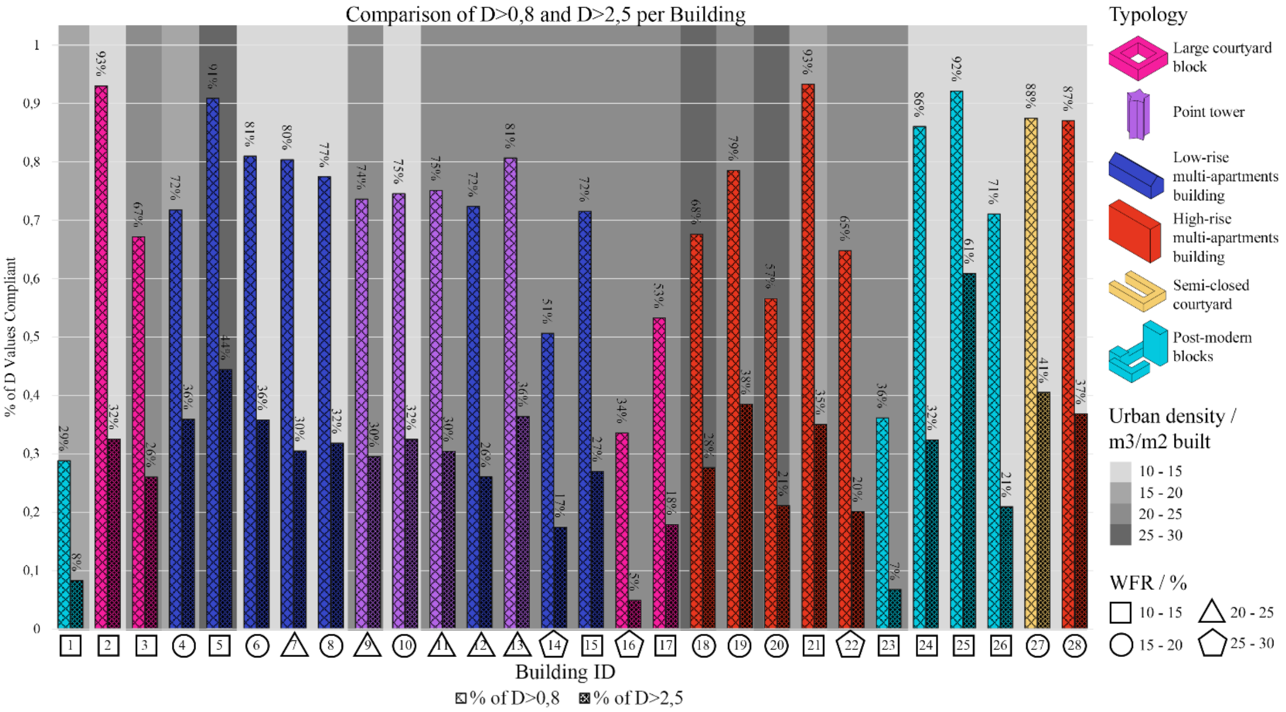


Figure 10 Compliance percentages for D metric by building and typology.

4.1.3 Energy and overheating in summer months.

When their performance regarding energy is simulated, none of the buildings in the sample achieve an energy class better than E. In fact, many of them are characterized as F and G, which are the worst possible energy classes. This is likely linked to the high U-value of some constructions, as well as the high U-value of the double-pane window used for the simulations of the base case.

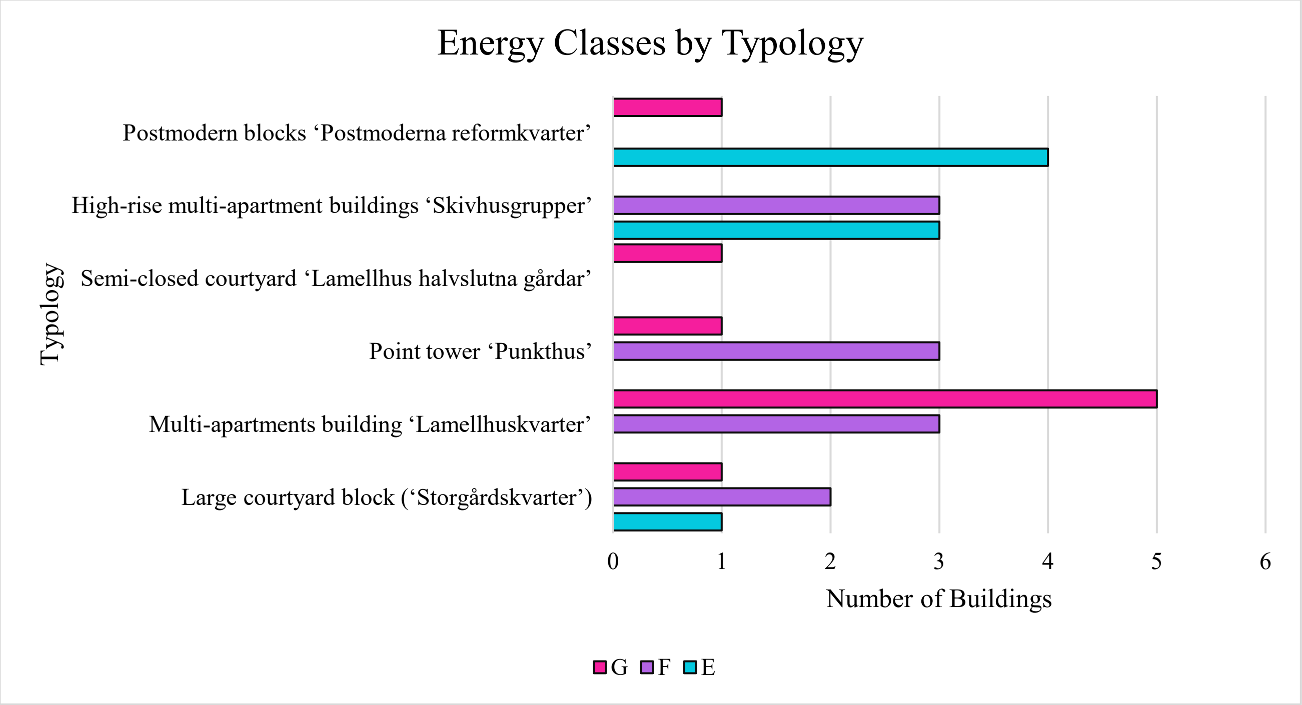


Figure 11 The energy classes of the buildings, grouped by typology.

As can be seen in Figure 11, the poorest performers from an energy perspective are low-rise multi-apartment buildings and point towers. This can be explained both by the age of these buildings, as well as the nature of the typologies themselves. On the one hand, these types of buildings tend to be older, and thus either uninsulated or have little insulation of rudimentary technology. On the other hand, they tend to stand alone in vast areas with sparse construction. As they are exposed on all sides, thermal losses would naturally be higher than typologies that are embedded in the urban fabric and share one or more walls with neighboring buildings. This is further emphasized when looking at this second kind of typologies; courtyard and postmodern blocks present lower EP_{pet} numbers, thus achieving better energy classes. Postmodern blocks in particular are also insulated better, as they are often built with more technologically advanced means and construction elements.

High-rise multi-apartment buildings present a kind of "middle of the road" situation. These kinds of buildings were built over an extended period of time and thus became a ground for experimentation and the application of new construction ideas and technologies. They are just as exposed as multi-apartment buildings and towers, but their higher floors often receive high solar gains, thus limiting heating needs. Thus, a more varied energy efficiency behavior makes sense for this typology.

In Sweden, it is not recommended that the operative temperature of an indoors area exceeds 26 ˚C during the summer (Folkhälsomyndigheten, 2024). A värmebölja, heatwave, is defined by the Swedish Public Health Agency (Folkhälsomyndigheten) as a period of at least three consecutive days with maximum daily temperatures above 26 °C. Prolonged heatwaves can affect indoor temperatures, and are dangerous for public health, especially when it comes to vulnerable groups. (Folkhälsomyndigheten, 2023) Thus, for a closer evaluation of the conditions of the buildings in the sample, the overheating hours, that is to say, the hours when operative temperature in an energy zone exceeds 26 ˚C, of each energy zone during the period April – September are also examined. Additionally, as defined in FEBY Kravspecifikation för Passivhus (Erlandsson, et al., 2009), the operative temperature of an indoors space may not be higher than 26 ˚C for more than 10% of the total hours in the period April – September. This limit is useful as a benchmark for characterizing the quality of the indoor environment of each building. Thus, it is used as a metric in this project to differentiate between energy zones overheating or not during the summer.

A closer look at the overheating of each energy zone can be seen in Figure 12, where the average overheating hours of all zones in each building are presented.

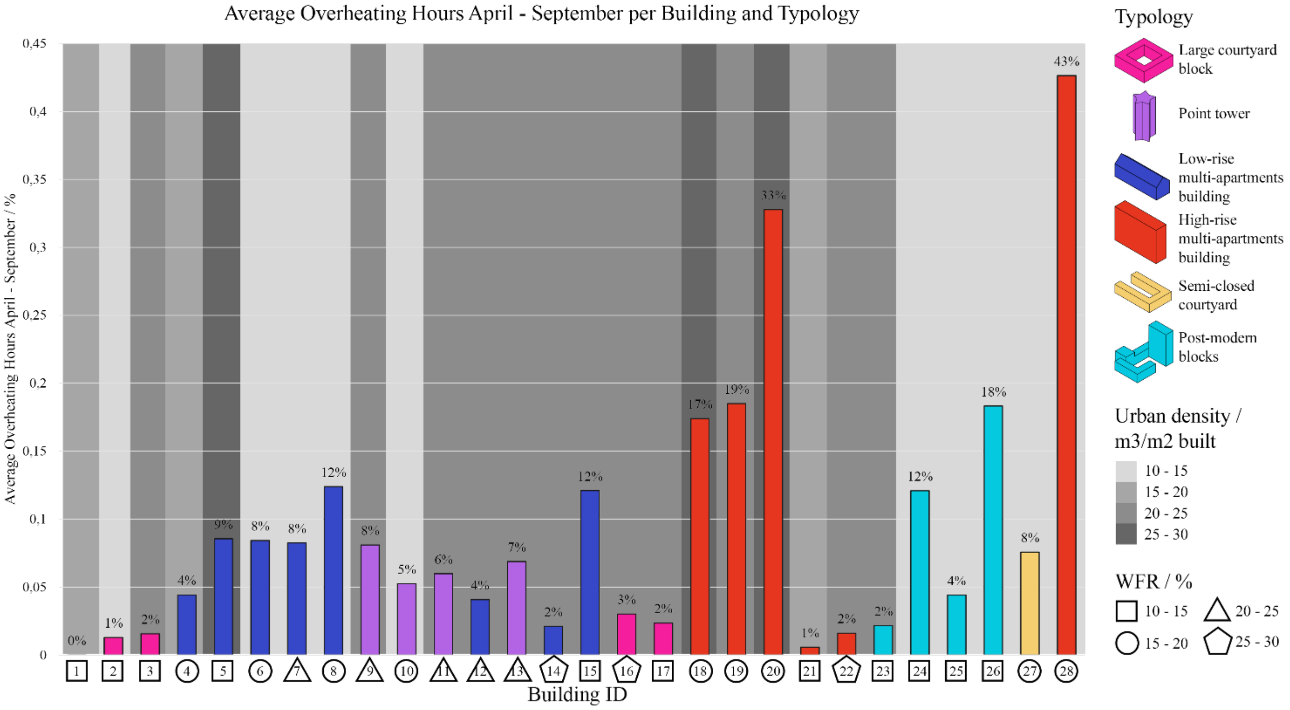


Figure 12 The average overheating hours per building and typology.

Comparing Figure 7 and Figure 12 it is possible to spot some similarities between daylighting and overheating results. High rises and postmodern blocks present high variation in their overheating behavior, similarly to how they behave when it comes to daylighting. However, elevated levels of compliance with the European Daylight Standard do not seem to directly lead to more zones overheating.

4.1.4 Statistical analysis of base case daylight results

The values of the three examined confounding variables of urban density (measured in m^3/m^2 built), average room depth (in m) and WFR are presented per building in Table 22 in Appendix A – Tables and figures.

To examine whether and to what extent these variables influence compliance with the European Daylight Standard, Pearson and Spearman correlation coefficients were calculated between each of these three variables and compliance levels to the standard. The results are presented in

Table 12 Pearson and Spearman correlation coefficients and respective p values for each of the three chosen confounding variables.

Confounding variable	Pearson r	Pearson p	Spearman r	Spearman p
Urban density	-0,293	0,13	-0,269	0,166
Room depth	-0,219	0,264	-0,195	0,321
WFR	-0,185	0,346	0,043	0,828

While none of the correlations are statistically significant at the 95% confidence level, weak to moderate negative trends are observed for both urban density and room depth, suggesting that denser contexts and deeper rooms may be associated with lower daylight performance. WFR, on the other hand, shows negligible correlation with compliance.

4.1.5 Verification of base case primary energy numbers

To evaluate the accuracy of the energy simulations, the simulated primary energy numbers for all 28 buildings are compared to the declared numbers from official Swedish energy declarations. Table 23 in Appendix A – Tables and figures presents a side-by-side comparison, including simulated and declared figures, as well as the percentual deviation.

The distribution of deviations observed is as follows: 12 buildings present deviations within 10%, 23 buildings present deviations within 20%, and 26 buildings present deviations within 30%. 2 buildings present deviations higher than 30%. Given their construction period, it is highly likely that these significant deviations are due to energy renovation conducted at a later date.

These figures suggest a generally good agreement between simulated and declared values, especially considering that energy performance simulations often exhibit deviations of up to ±30% from measured data in real-world cases (Coakley, Raftery, & Keane, 2014). These deviations can arise due to uncertainties in input data, weather files, occupant behavior, and operational conditions, all of which are known limitations in building performance simulation.

To further quantify the overall accuracy, the Mean Absolute Percentage Error (MAPE) was calculated, yielding a value of 26.9%. While this error level is not negligible, it is within acceptable bounds for early-stage performance modeling and comparative studies, particularly when involving older building stock with varied and partially unknown construction characteristics (Judkoff & Neymark, 2006)

In conclusion, while the model cannot replace calibrated or as-built simulation for design or certification purposes, it offers a valid approximation of building-level performance. The verification supports the use of this modeling methodology for trend analysis, typology comparisons, and the evaluation of daylight-energy interactions in Swedish residential buildings.

4.2 Renovation and low-e case results

Five buildings are selected for the testing of two renovation cases, one where the windows are enlarged and the same glazing assembly is kept, and second case where, in addition to enlargement a more advanced triple glazed low-e assembly was also installed. These buildings represent the five main typologies encountered in the sample and had a compliance of less than 20% with the European Daylight Standard Illuminance Criterion. No other buildings were tested due to time constraints. Semi-closed courtyards were excluded as only one such building is found in the sample, and it already presents quite a high rate of compliance.

A complete summary of the results for daylight and energy simulations for both renovation and low-e cases can be found in Table 24 and Table 25 in the Appendix.

Each of the buildings tested in the renovation and low-e cases is analyzed in detail in Figures 21 – 30 and Tables 26 – 30 in Appendix C – Detailed building information. Specifically, Figures 21, 23, 25, 27 and 29 illustrate spatial heat maps of the $sDA_{300,50}$ and $sDA_{100,50}$ metrics for the bottom and top floors of each building, for both base and renovation / low-e cases. The increase in daylight availability in renovations / low-e cases is apparent in all buildings. However, it can be noted that courtyard typologies present a lower increase than other kinds, especially high-rises and towers.

4.2.1 Daylighting simulation results, comparison with European Daylight Standard benchmarks, daylight factor

As can be seen in Figure 13, increasing the window area of the five selected buildings lead to an increase in compliance with the European Daylight Standard. However, this increase is different for different typologies.

The smallest improvement is observed in buildings 1 and 16, which are both courtyard typologies situated in dense urban areas. Thus, even with bigger windows, the solar gains are limited due to shading from surrounding structures. Buildings 10 and 22 are located in areas with sparse construction, and are freestanding, which results in a sizeable increase in solar gains. While the urban surroundings of Building 22 can be characterized as dense, the distance between buildings is large, which may explain the high compliance level achieved by enlarging the windows. Building 14 presents an in-between situation, as it is found in a somewhat dense area, but is similar in form to 10 and 22.

More details about the compliance rates to the specific parts of the Illuminance and D criteria of the European Daylight Standard can be found in Figure 20 in the Appendix.

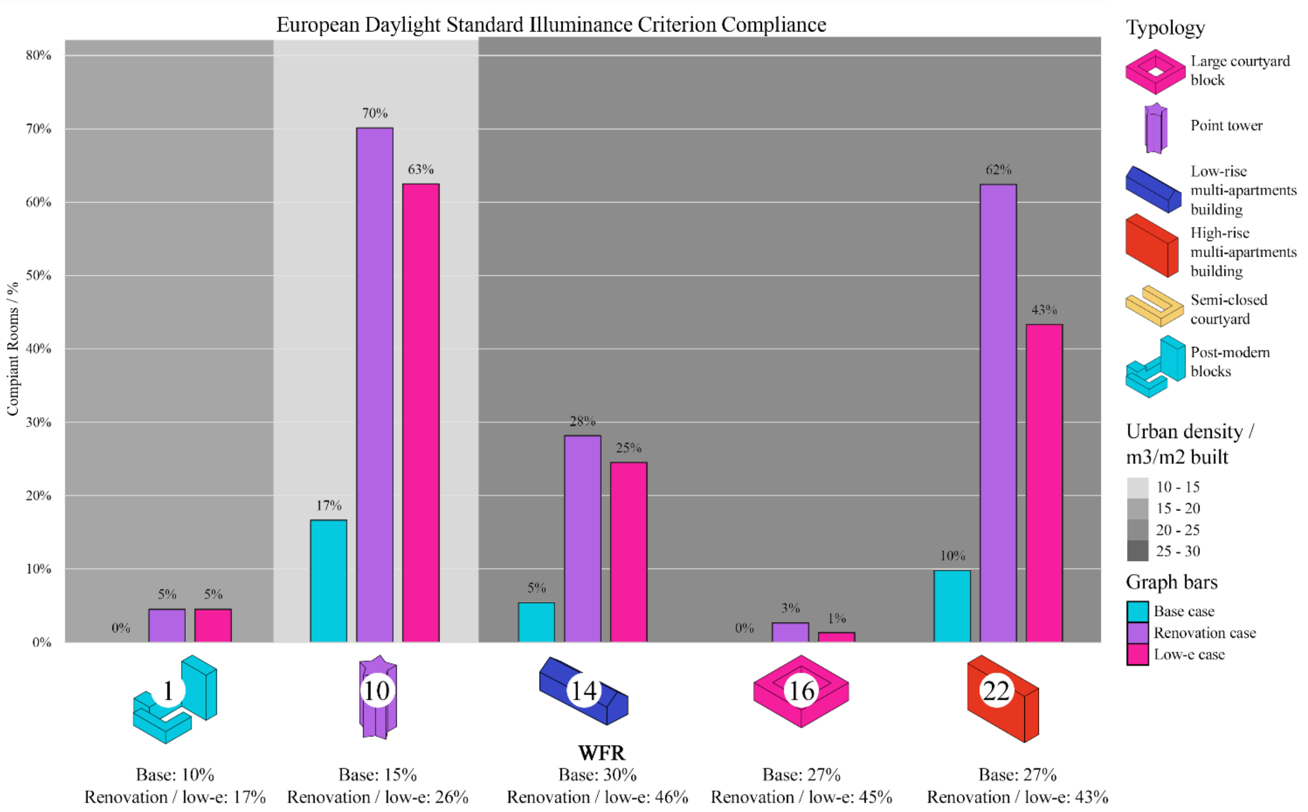


Figure 13 The European Daylight Standard Illuminance Criterion compliance percentages of each building by case.

4.2.2 Energy and overheating in summer months.

As per Table 24, it can be observed that the EP_{pet} of the chosen buildings remains about the same in the base and renovation cases. This is explained by the fact that, while the solar gains are increased in the renovation case, so are the heat losses through the windows, which have a rather high U-value as the assembly is not altered. In the low-e case, however, there are significant improvements when it comes to EP_{pet}. One of the buildings is awarded a better energy class, moving from F to E, just by installing window assemblies with a better U-value. Given the fact that it is possible to have very similar T_{vis} on the low-e assembly as in the base case one, such an assembly would be quite advantageous for energy renovation.

Overheating follows a similar trend. As made evident in Figure 14, the much higher solar gains in renovation case led to higher overheating in all buildings, although each building faces an increase of different intensity. Building 1 is a notable exception to this: it suffers almost no overheating in any case. The biggest increase is observed in building 10, which, while in the base case overheats on average 5,3% of the time in the summer, that number increases to 16,3% in the renovation case. It is a bit lower, 12,3%, if low-e assemblies are installed instead.

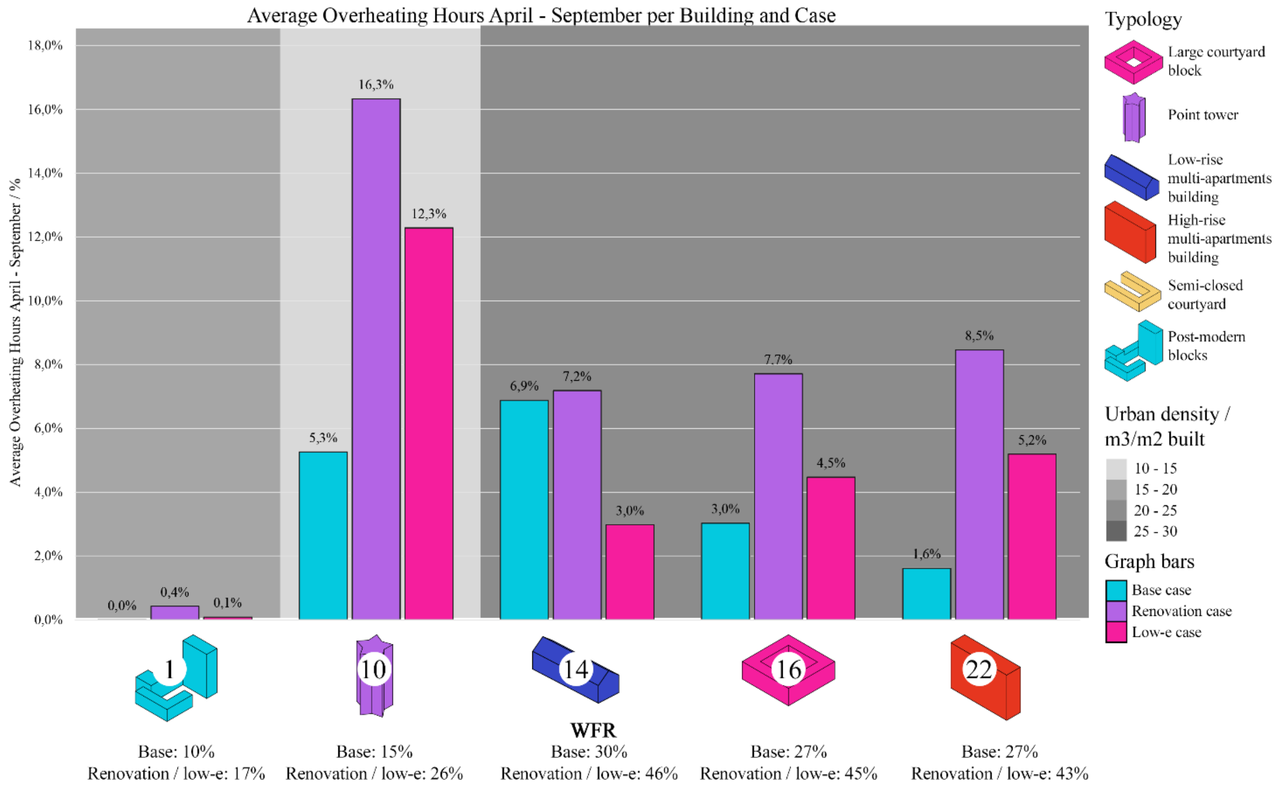


Figure 14 A bar chart of the average overheating hours in each building, presented grouped per case.

5 Discussion

Daylight provision and solar gains in buildings are dependent on a multitude of parameters. Building form, orientation, the density of the surrounding environment, location, local climate and microclimate are only some of them. In this project, by keeping to similar locations and climates, the importance of form typology, urban density and, to a certain extent, construction methods became apparent.

The different typologies that are encountered in the Swedish architectural context have different behaviors when it comes to daylighting, energy use and overheating issues. Urban typologies such as courtyard and postmodern blocks are reasonably protected from overheating and high energy use, thanks to the shading from the surroundings and their proximity to other construction. (Strømann-Andersen & Sattrup, 2011) However, the potential to increase solar gains and daylighting for these forms is small, when relying on conventional means such as increasing the window size (Dubois, 2025). It is possible that innovative solutions, such as façade materials with high reflectance, would contribute positively to increasing the availability of daylight in the interior spaces of such typologies.

On the other hand, it is worth noting the unpredictable behavior of high-rise buildings, regarding most of the parameters simulated in this project. Due to them being more exposed and usually situated in expansive park environments with sparse construction, the potential for solar gains is high in this typology, especially on higher floors. That often correlates with higher overheating, but not always, as these buildings are so susceptible to wind exposure and the particular shading patterns from their specific environment. (Habitzreuter, Smith, & Keeling, 2019) They are apparently also more sensitive to alterations such as increasing their glazing area; this way there is a lot of potential for more access to daylight, but it is also much easier to end up with dangerously overheated indoor spaces.

As per 4.1.4, compliance to the European Daylight Standard is found to correlate negatively with primarily urban density and room depth, and to a negligible degree with WFR. The statistical significance of these trends is low in the present study, however, similar trends have arosen in past studies with larger samples (Bournas & Dubois, 2019) that presented higher levels of statistical significance.

Fenestration assemblies also prove to be integral to managing and balancing daylighting, energy performance and overheating. Larger windows may offer the potential of higher solar gains, but a less insulating assembly may undo the advantages of that by introducing high energy losses. Thus, the impact on the building's energy efficiency may be negative. Modern technology offers the possibility of achieving high daylighting performance and good color rendering even when using techniques such as triple glazing and low-e membranes to mitigate heat losses.

In this particular thesis project, aside from simulating the effects of resizing the windows on the daylighting of different building typologies, the influence of glazing properties on energy use, overheating, and daylight availability was also examined. The renovation case windows, standard double-glazed assemblies with a U-value of 3,11 W/m^2K, a g-value of 0,75, and a T_{vis} of 0,7, are compared with the low-e case windows, triple-glazed assemblies with one argon-filled air gap and a low-e treatment on the inside of the outermost pane, with a U-value of 1,15 W/m^2K (63% reduction), a g-value of 0,39 (48% reduction) and a T_{vis} of 0,65 (7% reduction).

Comparing between the renovation case and the low-e case makes it possible to isolate changes in window properties, as the influence of other parameters such as window size, building geometry, or building orientation, on daylight availability are eliminated. When switching from the renovation assemblies to the low-e assemblies, consistent reduction of the primary energy numbers of the simulated buildings, their total solar heat gains, and the average overheating hours experienced during the summer is observed. Specifically, the lower U-value reduces conductive heat loss through the window, while the lower g-value reduces solar heat gains, particularly during the summer.

Comparing the data presented in Table 24 and Table 25, it can be calculated that the total solar heat gains are reduced by approximately 52% across all buildings. This closely aligns with the 48% reduction of the windows' g-value. The geometry of the building, windows and surroundings are not changed between the renovation and low-e cases, and the only alteration is the glazing assembly. Thus, the consistency of the solar heat gain reduction confirms the dominant role of g-value in regulating solar transmission (Sadineni, Madala, & Boehm, 2011).

Reducing solar heat gains lead to changes in overheating and heating demand. As shown in Figure 14, installing a triple glazed low-e assembly results in to a decrease of overheating hours in the summer, of about 3-4% for each building. Comparing the data presented in Table 24 and Table 25, it can be calculated that, between the renovation case and the low-e case, building yearly heating similarly shows a consistent reduction of 17-20%, and the EP_{pet} also improves by about 12-13%.

As the triple-glazed assembly has a lower T_{vis} than the double-glazed assembly, a lower percentage of rooms are compliant with the European Daylight Standard Illuminance in the low-e case than in the renovation case. However, this reduction in compliance is not consistent across all buildings, ranging in magnitude from 0% to 19%. This is likely due to each building's form and typology, which influences the distribution of the compliant rooms inside the building. Building 22, for example, which is a high rise, sees a reduction of 19% in compliance. Conversely, in buildings 1 and 16, courtyard typologies with already little daylight access on all their levels and rooms, a reduction of only 0% and 2% respectively in compliance is observed. This discrepancy could be attributed to the greater daylight exposure on the upper floors of building 22, which results in rooms exceeding compliance thresholds. When T_{vis} is reduced, these spaces' daylight access is affected to a greater degree, thus making them more likely to fall below compliance thresholds. The daylight availability of the top floor of building 22 is illustrated in Figure 34 in the Appendix.

Beyond window properties, the overall thermal performance of the buildings must also be considered. Several of the buildings examined here are quite poorly insulated, with high U-values for most of their construction elements, as seen in Table 20. These weakly performing elements—walls, roofs, slabs and thermal bridges—predictably lead to high energy use for heating, high EP_{pet} values, and excessive overheating during the summer. A renovation focused on the overall enhancement of the envelopes of these buildings and improving the U-values of their discrete construction elements may further aid reducing their energy use and improving their indoor climate. While examining window properties and evaluating their impact on energy use, thermal comfort and daylighting is the main focus of this thesis, in reality, it is multi-measure retrofits that lead to the greatest energy savings, because of synergies between energy effective components (National Center for Appropriate Technology (NCAT), 2025; Sadineni, Madala, & Boehm, 2011).

It is noteworthy that none of the buildings tested achieved 100% compliance with the European Daylight Standard, even after the alterations of the renovation and low-e cases that aimed at increasing daylight provision. When considering additionally the issues that arose in regard to energy consumption and overheating, it is made clear that adaptations are necessary for the standard to be relevant to the present condition of the European building stock.

At the same time, the low compliance observed, especially in buildings designed according to national standards such as the Swedish BBR, raises the question of whether these local daylight targets are truly sufficient to ensure daylight quality and promote health and well-being. While compliance is expected to drop when compared to significantly higher targets, this offers an opportunity to critically consider whether current national standards may be too modest. This reflection leads to a more nuanced discussion on whether the European Daylight Standard represents an unrealistic ideal, or if it is necessary rethinking of what constitutes sufficient daylight provision in residential settings.

Additionally, while the results of this research indicate that larger glazing areas inevitably lead to higher energy use and overheating, considering design quality and thoughtful use of passive strategies may refute this statement. Previous studies and demonstration projects have shown that, by utilizing well thought out passive measures, it is possible to consistently maintain indoor temperatures lower than outdoor ones. (Kutty, Barakat, & Khoukhi, 2023) This suggests that architectural solutions, such as orientation, shading, ventilation and thermal mass, can mitigate the risk of overheating even in buildings with generous daylight provision. Thus, even though they are not unrelated, the relationship between larger windows and overheating is not necessarily linear. Overall building design and the quality and thoughtfulness of passive measures utilized inform the nature of this relationship.

Ultimately, though, architectural and building design is permeated by a need to balance visual comfort, thermal comfort and energy efficiency. It is imperative to recognize that optimizing for one of those parameters will likely compromise another. A sustainable solution, therefore, may not necessarily be one that minimizes energy use at all costs, but instead maximizes indoor comfort while practicing responsibility regarding environmental impact.

6 Conclusions

This thesis aimed to examine the level of compliance of the residential building stock in Sweden with the European Daylight Standard. Through simulating daylight provision, energy use and overheating for 28 case study buildings, an understanding was developed regarding the levels of compliance of different typologies located in diverse environments. Additionally, the effect of measures aiming to increase daylight availability was examined.

None of the buildings tested achieved 100% compliance. The least compliant buildings needed to double their Window-to-Wall-Ratio to increase the compliance rate of rooms. In some cases, this measure could just increase compliance rates by few percent points, suggesting that building form and context, more than window size, are stronger determinants of daylight provision in some cases. However, the increase in window size has shown a dramatic decrease in thermal comfort, indicated by an increase in overheating hours well beyond the normally accepted 10% of hours during April-September.

The relationship between glazing and energy use is more complex than that of overheating or daylight. Larger windows introduce solar gains, but also thermal losses, especially if the glazing assembly has a high U-value. In this case, the best-case scenario is the energy use remaining the same but in many cases were shown to lead to a less energy efficient building. On the other hand, larger glazing areas combined with an insulating glazing assembly can drastically reduce energy use, as is clearly shown through Table 24 and Table 25.

On the other hand, summarizing the comparison between renovation case and low-e case, while a solution such as a the low-e case's triple-glazed assembly can yield substantial benefits when it comes to energy use and thermal comfort, these come at the cost of daylight availability. This is presented clearly through Table 24 and Table 25. As this trade-off is inevitable, a balance must be struck between these three parameters in the scenario of a retrofit. This must be done considering each individual case's broader context, such as typology, building form, glazing orientation, envelope performance and surroundings.

A suggestion can be made for context modifiers to the standard relating to surrounding urban density, building typology, room depth, and perhaps WFR, if subsequent studies establish a solid correlation trend between it and compliance to the European Daylight Standard. Changing recommendations depending on floor level may also be a clever idea, as lower floors receive truly little light, especially in high rise typologies.

These results suggest that current daylight requirements from the European Daylight Standard are simply impossible to reach. Even after renovating certain typologies of buildings, often at the expense of indoor thermal comfort, the European Daylight Standard's lowest recommended levels are too ambitious to be implemented in practice.

However, looking at the issue from another perspective, one may also raise the question of whether national daylight recommendations in Europe, such as Sweden's, are perhaps too modest to properly accommodate visual comfort and health. While a critical look upon the recommendations of the European Daylight Standard is required, a higher target level of daylight provision may also be a gateway and a provocation towards rethinking daylight quality in residential building design. Moreover, a higher level of expectations may be the necessary push for the European construction industry to adopt on a wider scale passive design strategies that manage thermal comfort alongside visual comfort. A healthy, pleasant and supportive indoor environment for occupants is just as important as energy targets, and truly sustainable building design must take that into account.

7 Limitations and future research directions

While this thesis offers insights into the applicability of the European Daylight Standard in the Swedish residential context, several limitations should be acknowledged. The primary constraint lies in the use of simplified assumptions for building constructions and systems. Due to the unavailability of detailed construction data for each case study, archetypical values were assigned based on typology and construction period. Although grounded in existing literature, these generalizations may introduce discrepancies between simulated and actual building performance. Similarly, assumptions about internal loads, occupant behavior, and absence of cooling or shading devices were necessary for model standardization but inevitably reduce the realism of individual cases.

Another key limitation stems from the focus on form and window geometry, and less attention paid to including dynamic shading devices. The utilization and schedule for the deployment of these in the simulation was deemed too unpredictable to include in a standardized method.

The daylight simulations, while comprehensive, rely on standardized climate files and do not account for interannual variability.

Energy verification was performed against declared energy data, which, although standardized, may include estimation errors or effects from undocumented renovations.

While several key confounding variables were identified and examined, the inherent complexity of energy and daylighting phenomena allows a lot of room for further exploration. Factors such as glazing and room orientation, specific shading patterns, surrounding building height, stratification of daylight access with building height, and others all provide fertile ground for future research.

Subsequent studies could employ calibrated models using measured data and as-built construction details to increase accuracy. The incorporation of dynamic façade technologies, occupant-responsive shading, and alternative glazing strategies could provide more insights into daylight-energy trade-offs. A thorough examination of the impact of more confounding variables is necessary, in order to achieve a deeper understanding of the phenomenon of daylighting in buildings. Moreover, extending the study across different climatic regions and building uses would help assess the broader applicability of EN 17037 and contribute to its refinement.

Finally, the methodology presented in this study could be repeated with a larger sample, in order to ensure the statistical significance of the simulated results and a more exact determination of trends and relationships between variables.

Appendix A – Tables and figures

Table 13 Recommendations of daylight provision by daylight openings in vertical and inclined surfaces. (Svenska Institutet för Standarder; European Committee for Standardization, 2021)

Level Of Recommendation For Vertical And Inclined Daylight Opening	**Target Illuminance Et Lx**	**Fraction Of Space For Target Level F_{plane},%**	**Minimum Target Illuminance Etm Lx**	**Fraction Of Space For Minimum Target Level F_{plane},%**	**Fraction Of Daylight Hours F_{time},%**
Minimum	300	50%	100	95%	50%

Medium	500	50%	300	95%	50%
High	750	50%	500	95%	50%

Table 14 The form typologies of the buildings and corresponding building IDs.

Form Typology	**Large Courtyard Block (Storgårdskvarter)**	**Multi-Apartments Building (Lamellhuskvarter)**	**Point Tower (Punkthus)**	**Semi-Closed Courtyard (Lamellhus Halvslutna Gårdar)**	**High-Rise Multi-Apartment Buildings (Skivhusgrupper)**	**Postmodern Blocks (Postmoderna Reformkvarter)**
Corresponding Ids	2, 3, 23, 24, 25, 26	4, 5, 6, 7, 8, 12, 14, 15	9, 10, 11, 13	27	18, 19, 20, 21, 22, 28	1, 23, 24, 25, 26, 27

Table 15 The construction typologies of each building and corresponding building IDs, part 1.

Construction Typology	**County Governor Houses, Younger (Landshövdingehus, Yngre)**	**Brick Houses, National Romanticism (Tegelhus, Nationalromantik)**	**Thick Houses, Brick (Tjockhus, Tegel)**	**Thin Houses, Brick (Smalhus, Tegel)**	**Low-Rise Multi-Apartment Buildings, Aerated Concrete (Lamellhus, Gasbetong)**
Corresponding Ids	3, 16, 17	2	14	4, 5, 6, 7, 8, 12, 15	27

Table 16 The construction typologies of each building and corresponding building IDs, part 2.

Construction Typology	**Low-Rise Multi-Apartment Buildings, Modular (Lamellhus, Elementbyggd)**	**Tower, 3 Floors, Aerated Concrete (Punkthus, 3 Våningar, Gasbetong)**	**Tower, 6 Floors, Brick (Punkthus, 6 Våningar, Tegel)**	**Tower, Lightweight Concrete (Punkthus, Lättbetong)**	**High-Rise Multi-Apartment Building, Lightweight Concrete (Skivhus, Lättbetong)**
Corresponding Ids	23	9	10	11, 13	18, 21, 22

Table 17 The construction typologies of each building and corresponding building IDs, part 3.

Construction Typology	**High-Rise Multi-Apartment Building, Modular Façade Elements (Skivhus, Fasadelement)**	**High-Rise Multi-Apartment Building, Modular (Skivhus, Elementbyggd)**	**Barge House, Lightweight Concrete (Burspråkshus, Lättbetong)**	**Courtyard Blocks, Concrete Frame (Kvartersstad, Betongstomme)**
Corresponding Ids	20, 28	19	1	24, 25, 26

Table 18 Geographic adjustment factor values according to location (Boverket, 2024)

Region	**Geografic Area, Municipality**	**Geografic Adjustment Factor, F_{geo}**
Stockholm	All municipalities	1,0

Västra Götaland	Göteborg, Härryda, Kungälv, Lerum, Lysekil, Mölndal, Orust, Partille, Sotenäs, Stenungsund, Strömstad, Tanum, Tjörn, Uddevalla and Öckerö	0,9
Örebro	Hallsberg, Kumla, Laxå, Lekeberg and Örebro	1,0

Table 19 Weighting factors by energy carrier (Boverket, 2024)

Energy Carriers	**Weighting Factor** (Vf_i)
Electricity (VF_{el})	1,8
District heating (VF_{fjv})	0,7
District cooling (VF_{fjk})	0,6
Solid, liquid and gaseous biofuels (VF_{bio})	0,6
Fossil oil (VF_{olja})	1,8
Fossil gas (VF_{gas})	1,8

Table 20 The U-values of each construction element of every simulation construction set.

Typology	**U-Values / W/m²K**							
	Exterior Wall	**Exterior Roof**	**Exposed Floor**	**Basement Wall**	**Basement Roof**	**Basement Floor**	**Interior Wall**	**Interior Floor/Ceiling**
County governor houses, younger (Landshövdingehus, yngre)	1,53	0,46	0,46	0,46	0,41	0,52	1,53	0,46
Brick houses, national romanticism (Tegelhus, nationalromantik)	2,01	1,82	1,82	2,71	3,15	3,15	2,01	3,75
Thick houses, brick (Tjockhus, tegel)	2,01	1,82	1,82	2,71	3,15	3,15	2,01	3,75
Thin houses, brick (smalhus, tegel)	2,26	1,08	1,08	2,71	0,79	3,15	2,26	0,75
Low-rise multi-apartment buildings, aerated concrete (Lamellhus, gasbetong)	2,24	0,93	0,93	3,75	0,79	4,65	3,75	0,79
Low-rise multi-apartment buildings, modular (Lamellhus, elementbyggd)	3,75	0,14	0,14	3,75	3,75	4,15	3,75	3,75
Tower, 3 floors, aerated concrete (Punkthus, 3 våningar, gasbetong)	1,72	0,20	0,20	3,15	0,25	4,65	2,26	0,25
Tower, 6 floors, brick (Punkthus, 6 våningar, tegel)	2,87	0,89	0,89	2,87	0,27	4,15	2,26	0,27
Tower, lightweight concrete (Punkthus, lättbetong)	2,33	0,20	0,20	2,20	0,27	4,65	3,75	0,27

High-rise multi-apartment building, lightweight concrete (Skivhus, lättbetong)	1,91	0,28	0,28	3,15	0,27	0,28	3,75	0,27
High-rise multi-apartment building, modular façade elements (Skivhus, fasadelement)	0,28	0,20	0,20	0,52	0,28	4,15	3,75	4,15
High-rise multi-apartment building, modular (Skivhus, elementbyggd)	0,28	0,14	0,14	0,28	3,75	3,15	3,75	3,75
Barge house, lightweight concrete (Burspråkshus, lättbetong)	1,21	0,10	0,10	1,21	3,15	3,75	4,15	3,15
Courtyard blocks, concrete frame (Kvartersstad, betongstomme)	0,14	0,14	0,14	0,14	3,75	3,75	0,28	3,75

Table 21 The summary of the results of the base case daylight and energy simulations.

ID	**EUI / kWh /m^2/yr**	**Building Yearly Heating / kWh**	**EUI Heating / kWh /m^2/yr**	**Ep_{pet} / kWh /m^2/yr**	**Energy Class**	**Daylight Standard Illuminance Criterion Compliant Rooms / %**	**Average Percentage Overheating Hours April - September**	**Total Solar Gains / kWh**
1	135,34	123 539 ,98	105,92	126,88	E	0,0%	0,0%	15 344 ,22
2	225,66	187 585 ,60	196,11	197,03	G	43,0%	1,3%	29 323 ,61
3	129,73	173 558 ,03	98,99	121,49	E	1,0%	1,6%	41 263 ,31
4	250,12	107 899 ,23	220,16	198,61	G	38,0%	4,4%	19 833 ,91
5	206,90	636 775 ,23	175,87	167,61	F	65,0%	8,6%	99 541 ,67
6	288,63	181 030 ,03	258,60	225,52	G	42,0%	8,4%	27 404 ,56
7	283,69	283,69	254,35	222,55	G	31,0%	8,3%	36 192 ,48
8	286,15	157 789 ,98	257,33	224,63	G	38,0%	12,4%	28 054 ,64
9	238,79	135 698 ,98	208,40	190,38	G	24,0%	8,1%	25 669 ,51
10	190,09	411 117 ,26	159,47	156,13	F	17,0%	5,3%	77 536 ,26
11	169,98	368 906 ,58	139,08	152,68	F	52,0%	6,0%	110 389 ,76
12	219,92	477 299 ,38	189,64	177,25	G	9,0%	4,1%	64 311 ,83
13	197,08	312 857 ,08	166,95	161,37	F	53,0%	6,9%	67 980 ,35
14	206,39	418 079 ,77	177,93	169,05	F	5,0%	2,1%	55 880 ,37

15	198,78	722 302 ,54	168,49	162,44	F	33,0%	12,1%	135 707 ,71
16	198,06	316 966 ,19	171,60	164,62	F	0,0%	3,0%	41 277 ,38
17	189,85	330 493 ,93	161,81	157,77	F	9,0%	2,4%	44 362 ,35
18	172,37	822 647 ,97	142,57	144,30	F	11,0%	17,4%	203 901 ,71
19	122,74	286 049 ,36	94,27	110,49	E	20,0%	18,5%	102 104 ,97
20	124,76	446 035 ,33	93,90	110,23	E	13,0%	32,8%	158 474 ,69
21	166,39	532 057 ,50	139,90	142,43	F	82,0%	0,6%	97 177 ,71
22	177,89	660 857 ,39	149,12	148,88	F	10,0%	1,6%	113 803 ,81
23	227,37	636 934 ,86	198,73	183,61	G	0,0%	2,2%	59 992 ,81
24	117,30	584 148 ,63	90,15	107,60	E	33,0%	12,1%	197 089 ,95
25	139,82	504 020 ,22	109,37	121,06	E	80,0%	4,4%	111 641 ,15
26	122,35	402 474 ,76	91,79	108,75	E	7,0%	18,3%	105 990 ,76
27	253,20	831 027 ,40	227,02	203,41	G	64,0%	7,6%	147 651 ,60
28	121,02	247 547 ,36	95,18	111,12	E	63,0%	42,6%	135 927 ,45

Table 22 The WFR, urban density, and average room depth per building.

Building ID	WFR / %	Urban density / m3/m2 built	Average room depth / m
1	10,0%	15,3	5,1
2	11,2%	10,4	4,9
3	12,9%	22,6	5,0
4	18,6%	15,1	3,9
5	13,3%	27,2	4,2
6	19,5%	13,4	3,6
7	20,3%	12,1	3,7
8	18,7%	11,4	3,6
9	22,5%	12,8	3,9
10	15,4%	14,3	4,0
11	17,5%	23,1	4,7
12	15,9%	21,1	4,6
13	17,0%	23,1	4,5
14	29,7%	20,4	3,8
15	13,6%	24,8	4,1
16	27,2%	21,7	4,4
17	13,1%	24,2	4,1
18	17,0%	29,0	4,7
19	15,3%	23,3	4,3
20	16,3%	25,7	4,1
21	14,9%	17,7	4,0

22	26,7%	19,5	4,5
23	14,2%	18,9	4,1
24	13,7%	11,0	3,9
25	14,3%	10,5	4,3
26	13,1%	13,4	4,3
27	18,0%	14,4	4,4
28	16,0%	10,1	4,1

Table 23 Side-by-side comparison of the simulated and declared primary energy numbers for each of the 28 buildings, along with their calculated percentual deviation.

Building ID	Simulated Primary Energy Number / kWh/m2/year	Declared Primary Energy Number / kWh/m2/year	Percentual Deviation / %
1	126,88	135	6%
2	197,03	166	-16%
3	121,49	133	9%
4	198,61	98	-51%
5	167,61	137	-18%
6	225,52	191	-15%
7	222,55	168	-25%
8	224,63	164	-27%
9	190,38	46	-76%
10	156,13	140	-10%
11	152,68	133	-13%
12	177,25	149	-16%
13	161,37	137	-15%
14	169,05	161	-5%
15	162,44	173	7%
16	164,62	141	-14%
17	157,77	148	-6%
18	144,3	143	-1%
19	110,49	134	21%
20	110,23	125	13%
21	142,43	153	7%
22	148,88	183	23%
23	183,61	170	-7%
24	107,6	118	10%
25	121,06	128	6%
26	108,75	121	11%
27	203,41	212	4%
28	111,12	115	3%

Table 24 The summary of the results of the renovation case daylight and energy simulations.

ID	EUI / kWh /m^2/yr	Building Yearly Heating / kWh	EUI Heating / kWh /m^2/yr	Ep$_{pet}$ / kWh /m^2/yr	Energy Class	Daylight Standard Illuminance Criterion Compliant Rooms / %	Average Percentage Overheating Hours April - September	Total Solar Gains / kWh
1	140,47	129 516 ,06	111,04	130,86	E	5%	0%	25 527 ,87
10	189,73	410 192 ,74	159,11	155,88	F	70%	16%	125 930 ,18
14	207,12	419 808 ,38	178,66	169,56	F	28%	7%	82 028 ,39
16	200,88	322 172 ,12	174,42	166,59	F	3%	8%	67 314 ,61
22	175,51	650 337 ,31	146,74	147,22	F	62%	8%	183 678 ,45

Table 25 The summary of the results of the low-e case daylight and energy simulations.

ID	EUI / kWh /m^2/yr	Building Yearly Heating / kWh	EUI Heating / kWh /m^2/yr	Ep$_{pet}$ / kWh /m^2/yr	Energy Class	Daylight Standard Illuminance Criterion Compliant Rooms / %	Average Percentage Overheating Hours April - September	Total Solar Gains / kWh
1	118,18	103 522 ,97	88,75	113,53	E	5%	0%	12 256 ,74
10	161,79	338 150 ,14	131,17	136,32	F	63%	12%	60 478 ,60
14	178,85	353 387 ,83	150,40	149,78	F	25%	3%	39 434 ,29
16	172,64	270 016 ,10	146,18	146,83	F	1%	4%	32 366 ,43
22	150,70	540 376 ,08	121,93	129,85	E	43%	5%	88 133 ,64

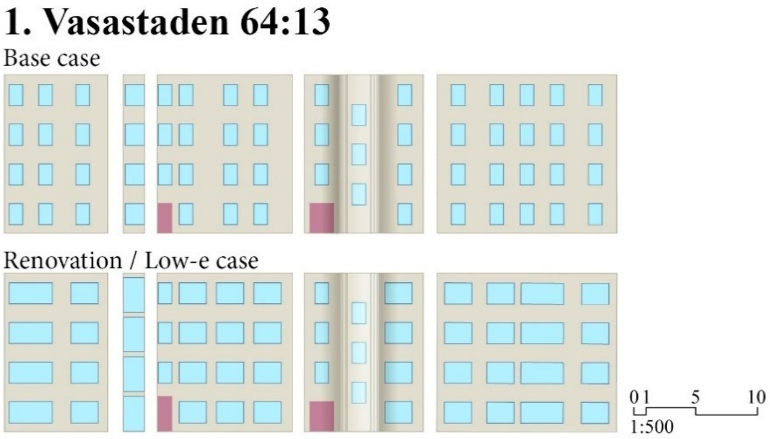


Figure 15 The facades of Vasastaden 64:13. Top: Base case, bottom: renovation and low-e cases.

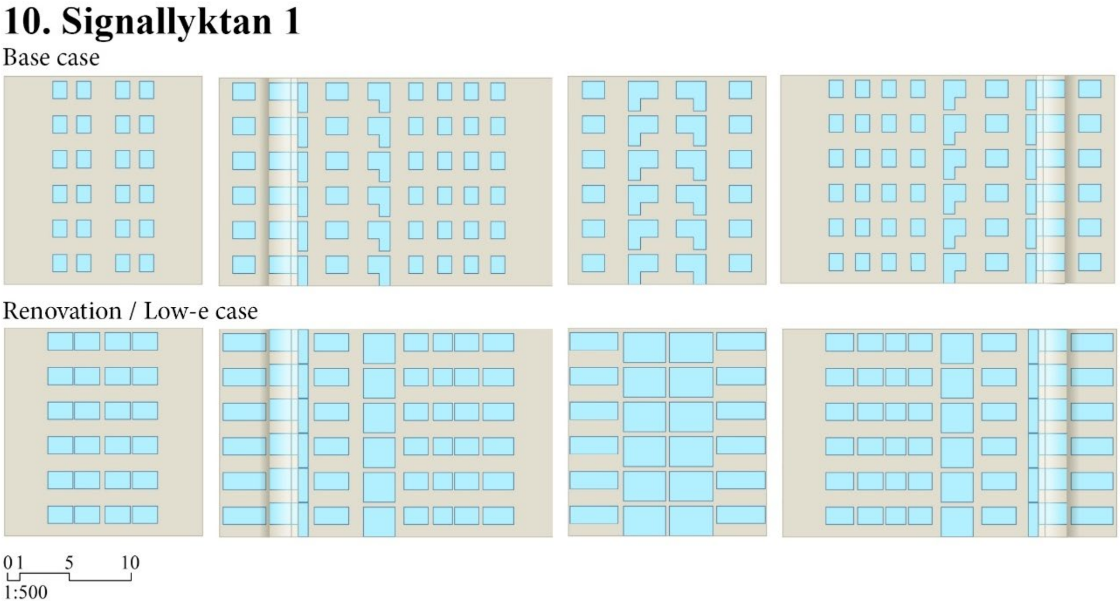


Figure 16 The facades of Signallyktan 1. Top: Base case, bottom: renovation and low-e cases.

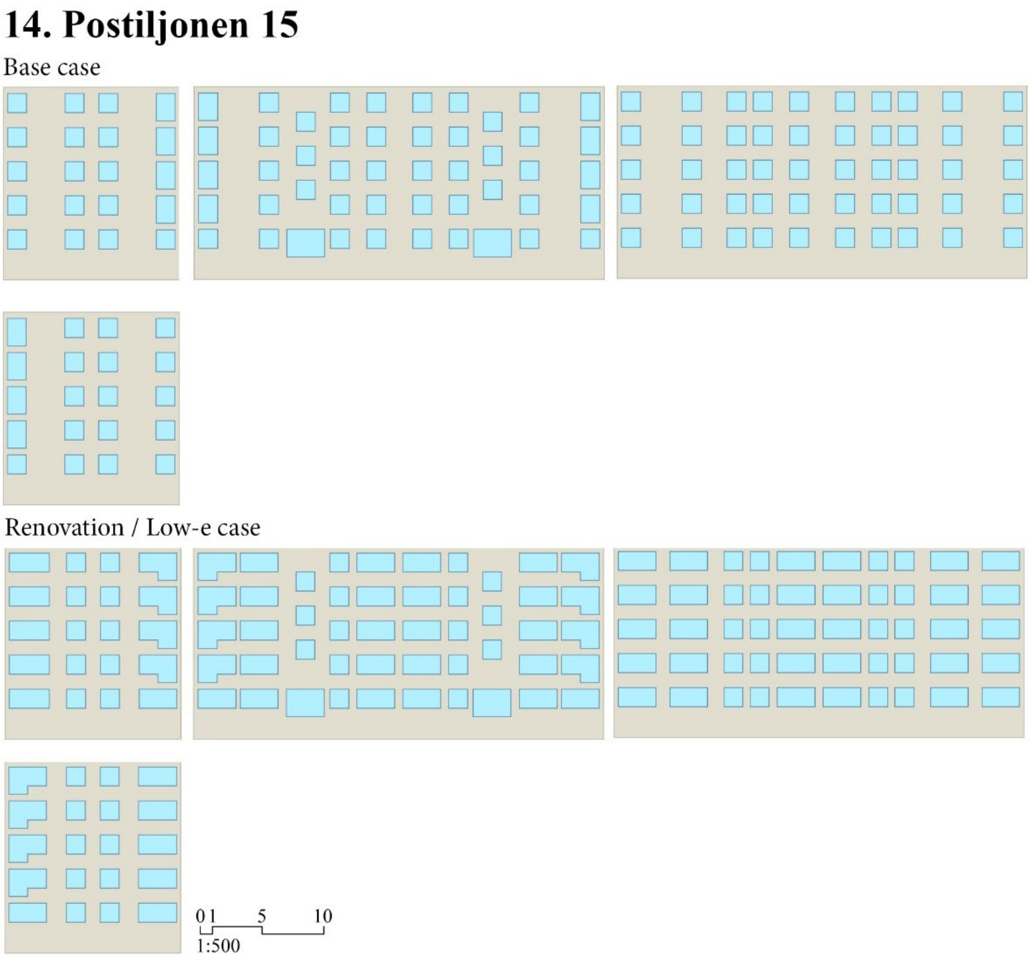


Figure 17 The facades of Postiljonen 15. Top: Base case, bottom: renovation and low-e cases.

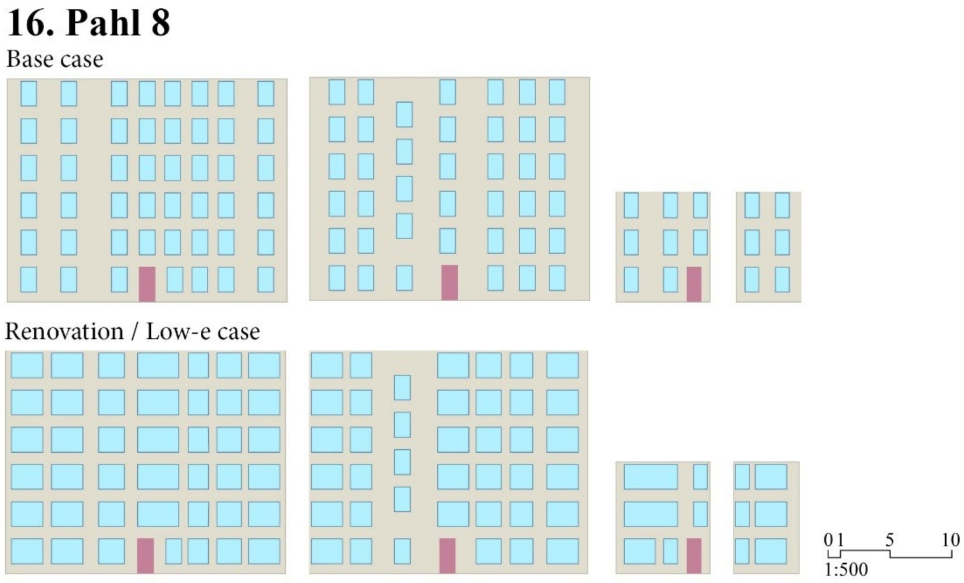
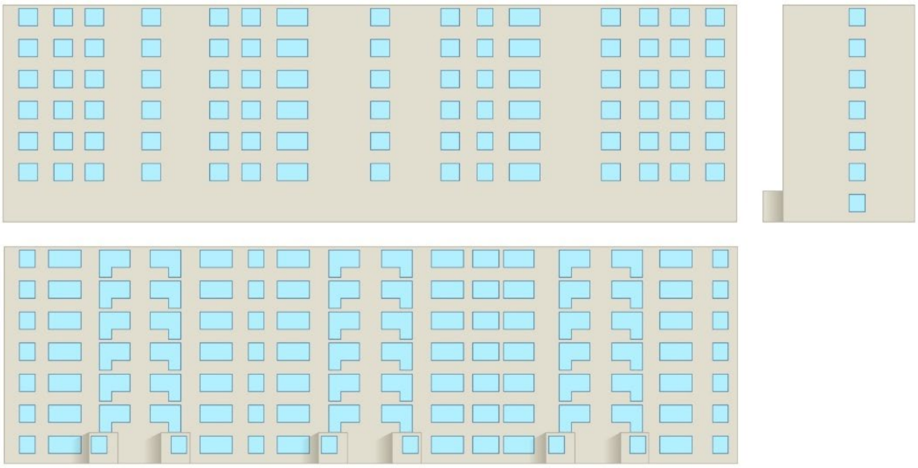


Figure 18 The facades of Pahl 8. Top: Base case, bottom: renovation and low-e cases.

22. Branthomen 1:2

Base case



Renovation / Low-e case

Figure 19 The facades of Brantholmem 1:2. Top: Base case, bottom: renovation and low-e cases.

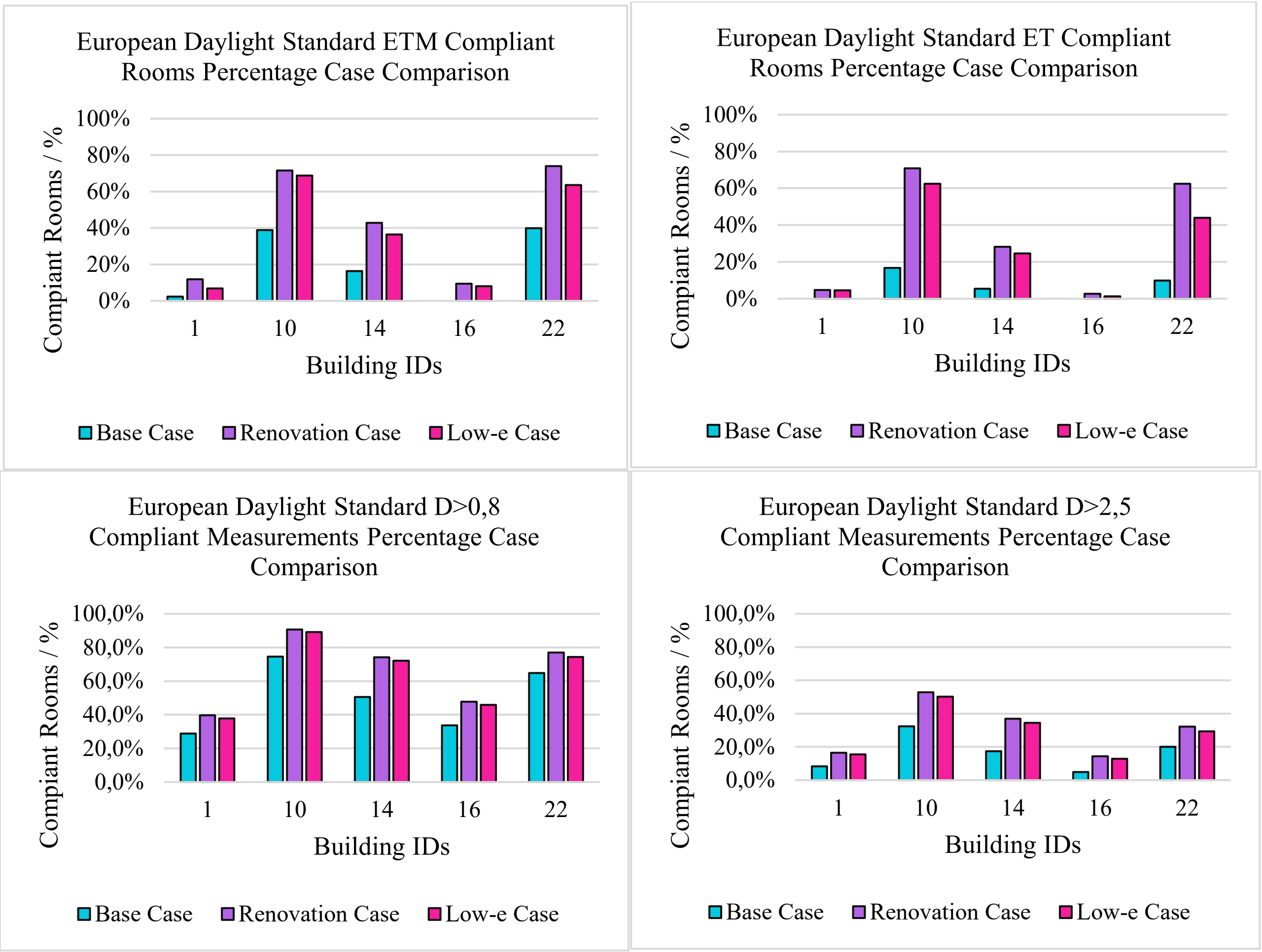


Figure 20 Detailed compliance percentages for the European Daylight Standard.

Appendix B – Detailed construction typologies

County governor houses, younger (Landshövdingehus, yngre)

Constructed during a longer period, from 1880 to 1940, these houses present great variation in their formation but are generally comprised of a stone ground floor (either painted or clad in bare brick) and a wooden superstructure. They could be part of a courtyard or arranged in parallel volumes, according to modernistic ideals. Window designs are simple, usually separated into 6 panes.

Brick houses, national romanticism (Tegelhus, nationalromantik)

This building style, originating under World War I, is inspired by older Swedish and German traditions. These buildings are made mainly of brick, while some concrete is used in the slabs. The entry halls are decorated with stone reliefs. Windows can be rectangular or arched, split into several small panes.

Thick houses, brick (Tjockhus, tegel)

A type of house developed by HSB and constructed under the period, 1920 – 1940, these are made of a combination of brick and some concrete, mostly for the basement. Thick houses are deep, usually 14 – 16 m, rectangular in shape and built in parallel arrangements, and contain apartments that surrounded a central circulation area. The apartments are often small, although well-equipped for their time. They tend to be quite dark. Windows are simple, split vertically into three or four panes.

Thin houses, brick (smalhus, tegel)

These were much more popular than thick houses, and in the end outcompeted them. Popular mainly under the 30s, their construction method and materials are similar to thick houses, but their depth is reduced to around 8 m, thus achieving much better daylighting conditions inside. The rectangular volumes are arranged in parallel, much like their predecessors.

Low-rise multi-apartment buildings, aerated concrete (Lamellhus, gasbetong)

This form was popular from the 40s to the 60s, and can be found everywhere in Sweden. As previous ideas about courtyards re-emerged at the time, these buildings are often arranged in these formations. As their name suggests, they are made of mostly aerated concrete in the form of lightweight blocks. They are up to three floors high, and often have balconies. The ground floor is often one short set of stairs up from street level. Simple window designs are the rule here.

Low-rise multi-apartment buildings, modular (Lamellhus, elementbyggd)

Like other low-rise multi-apartment typologies in neighborhood planning and building design, the biggest difference that this type displays is its construction, as it is made of prefabricated sandwich-type (made of two slices of concrete with insulation sandwiched in-between) walls and other construction elements, that are carried to the construction site and assembled in-situ. Three-pane glass is used for the windows. The modular nature of these houses is apparent in their facades, as one can often distinguish the seams where the elements attach to each other. They were constructed from the late 60s to the early 80s.

Tower, 3 floors, aerated concrete (Punkthus, 3 våningar, gasbetong)

This is a type with construction similar to low-rise multi-apartment buildings, aerated concrete, but with significant typological differences relating to form. They are more compact, often have more floors (from three to five, although the earliest ones that do not have an elevator, are on the shorter side), and usually only have one stairwell. They are exposed on all four sides and usually their longest axis aligns with the north-south orientation. They are often built in smaller plots of land, and were commonly constructed in the period 1940 - 1960.

Tower, 6 floors, brick (Punkthus, 6 våningar, tegel)

When, towards the end of the 30s, the elevator became a more common addition to buildings, the height of towers increased to 6 – 8 floors. The walls of these buildings are made of brick-clad concrete, and the slabs of concrete are clad with wooden planks, often with insulation underneath.

Tower, lightweight concrete (Punkthus, lättbetong)

In the 50s and 60s towers were one of the most popular multi-family typologies in Sweden. Thanks to the elevator being common, their height most often exceeds 6 floors. They are built in many different ways, and at the time had become a fertile ground for building technology experiments. This type is comprised of concrete walls and slabs, usually poured in-situ instead of being prefabricated. Lightweight concrete blocks are also popular for certain construction elements.

High-rise multi-apartment building, lightweight concrete (Skivhus, lättbetong)

This typology appeared in the 60s in order to solve Sweden's growing housing shortage. Similarities are observed between it and modernistic typologies that appeared in other countries during that time, which is to say, gigantic building volumes placed in vast park environments. Lightweight concrete blocks are used for the walls and reinforced concrete for the slabs. This building type is often synonymous with Sweden's Million Houses Program (Miljonprogram). 8 – 9 floors is a common height.

High-rise multi-apartment building, modular façade elements (Skivhus, fasadelement)

Similar to the aforementioned typology when it comes to form and area planning, this is an evolution regarding construction. As the Million Houses Program demanded short construction times and efficient methods, the construction process was further industrialized. Outer walls are made of prefabricated, room-sized elements, although inner walls and slabs are still poured in-situ.

High-rise multi-apartment building, modular (Skivhus, elementbyggd)

The next step in the evolution of the high-rise typology, almost all construction elements of this type are prefabricated. Concrete is used generously, and new types of synthetic materials are becoming popular, such as cellular plastic as insulation. The basement construction is still poured in-situ.

Barge house, lightweight concrete (Burspråkshus, lättbetong)

This typology was developed towards the end of the 70s and was utilized mainly for densifying the outer parts of city centers. While the buildings are arranged to fit into the neighborhood-like environment from a planning perspective, the demands for an aesthetic that fit the older surroundings are heightened. The industrialized functionalism and efficiency of previous eras is left behind, and these new types are a lot more experimental in their aesthetics, sometimes even incorporating reused parts of older buildings. Concrete still dominates as a construction material, as outer walls are made of lightweight blocks, and slabs of reinforced concrete.

Courtyard blocks, concrete frame (Kvartersstad, betongstomme)

These buildings are clear expressions of the postmodern style and have a variety of aesthetics. They were most common during the 80s. Wall systems are starting to become popular, and more insulation is used than before, possibly due to the effects of the energy crisis of the 70s. Slabs and other bearing elements are made of reinforced concrete. The façade can be clad in varied materials, such as limestone or brick.

Low-rise multi-apartment buildings, concrete frame (Lamellhus, plattbärlag)

This type appeared in the 80s and spans all the way to the 2000s. It is quite similar to other low-rise multi-apartment types, but with a bearing system made of a combination of steel elements and reinforced concrete walls to offer rigidity. Wall systems are used for façade walls, with several layers of insulation.

Appendix C – Detailed building information

1. Vasastaden 64:13 Erik Dahlbergsgatan 12, Gothenburg. 1987. Postmodern block.

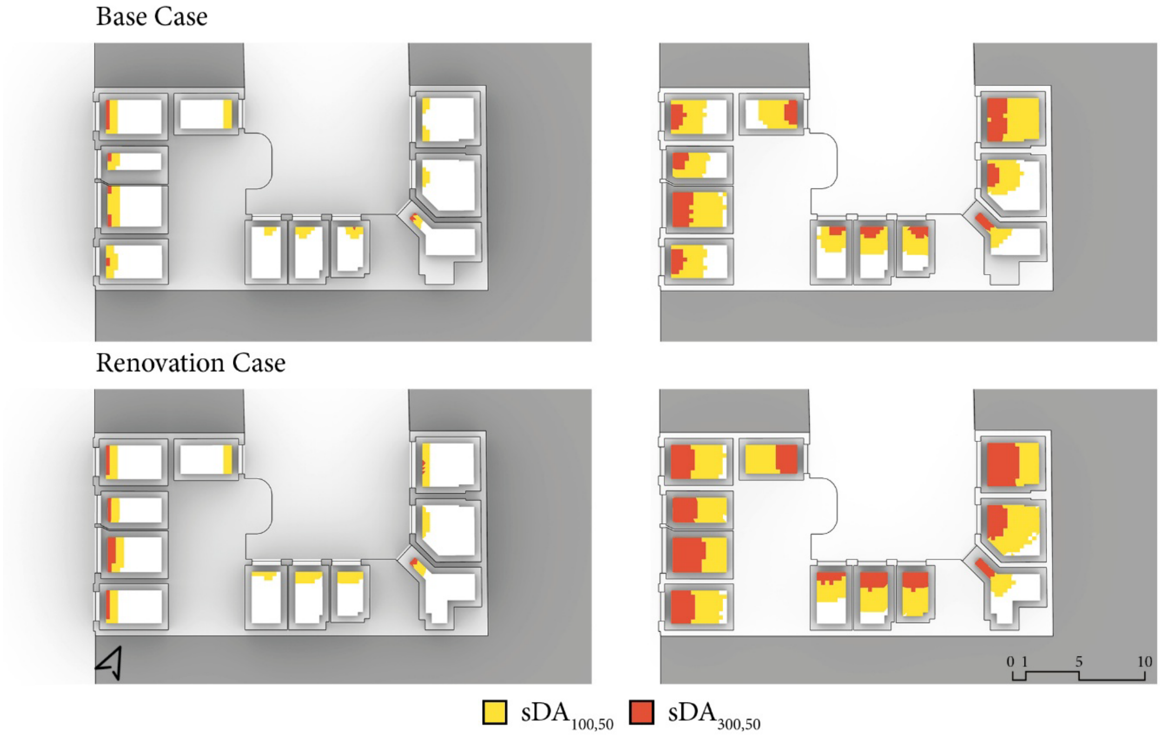


Figure 21 The sDA of all three cases tested. Left: ground floor, Right: top floor

Table 26 The EUI, EP$_{pet}$ and energy class of all three cases tested.

	Base Case	Renovation Case	Low-e Case
EUI / kWh/m2/year	135,34	140,47	118,18
EPpet / kWh/m2/year	126,88	130,86	113,53
Energy class	E	E	E

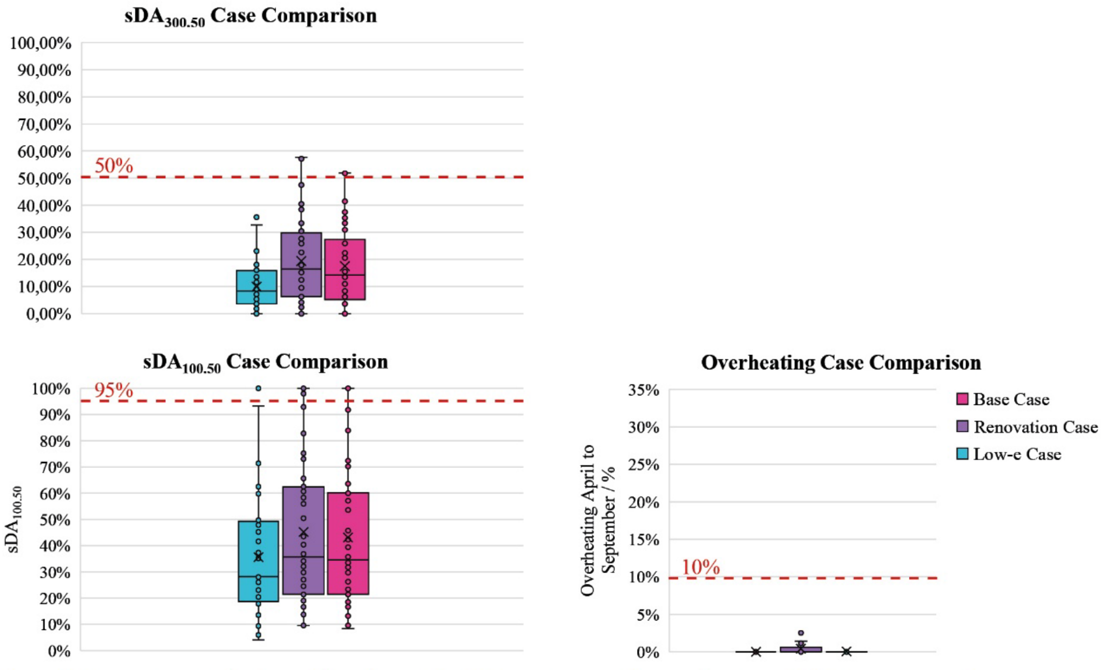
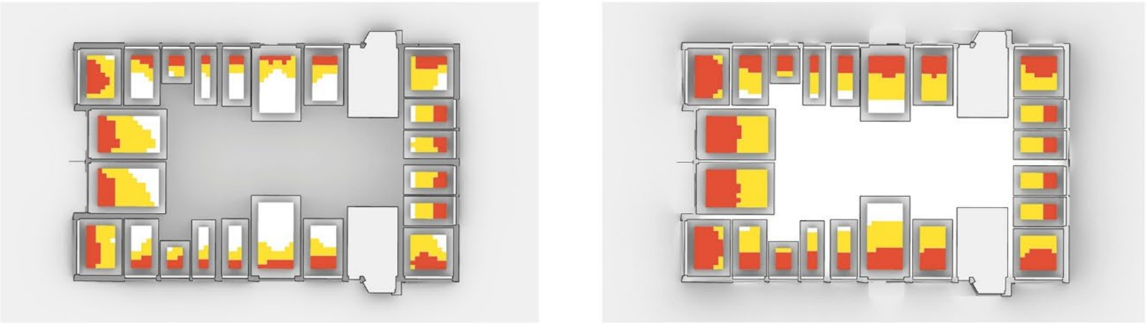


Figure 22 Comparison, in the form of box plots, of the sDA metrics, as well as overheating, of all three cases tested.

10. Signallyktan 1 Rålambsvägen 21, Stockholm. 1943. Point tower.

Base Case



Renovation Case

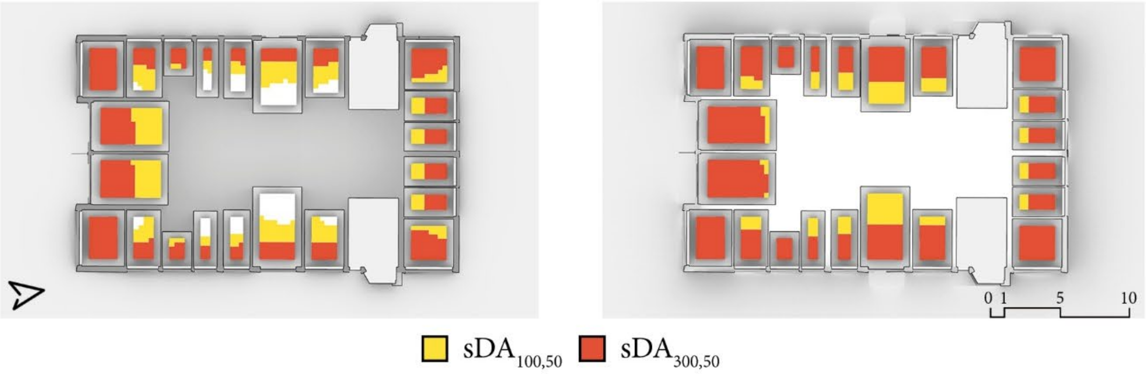


Figure 23 The sDA of all three cases tested. Left: ground floor, Right: top floor

Table 27 The EUI, EP_{pet} and energy class of all three cases tested.

	Base Case	**Renovation Case**	**Low-e Case**
EUI / kWh/m2/year	190,09	189,73	161,79
EPpet / kWh/m2/year	156,13	155,88	136,32
Energy class	F	F	F

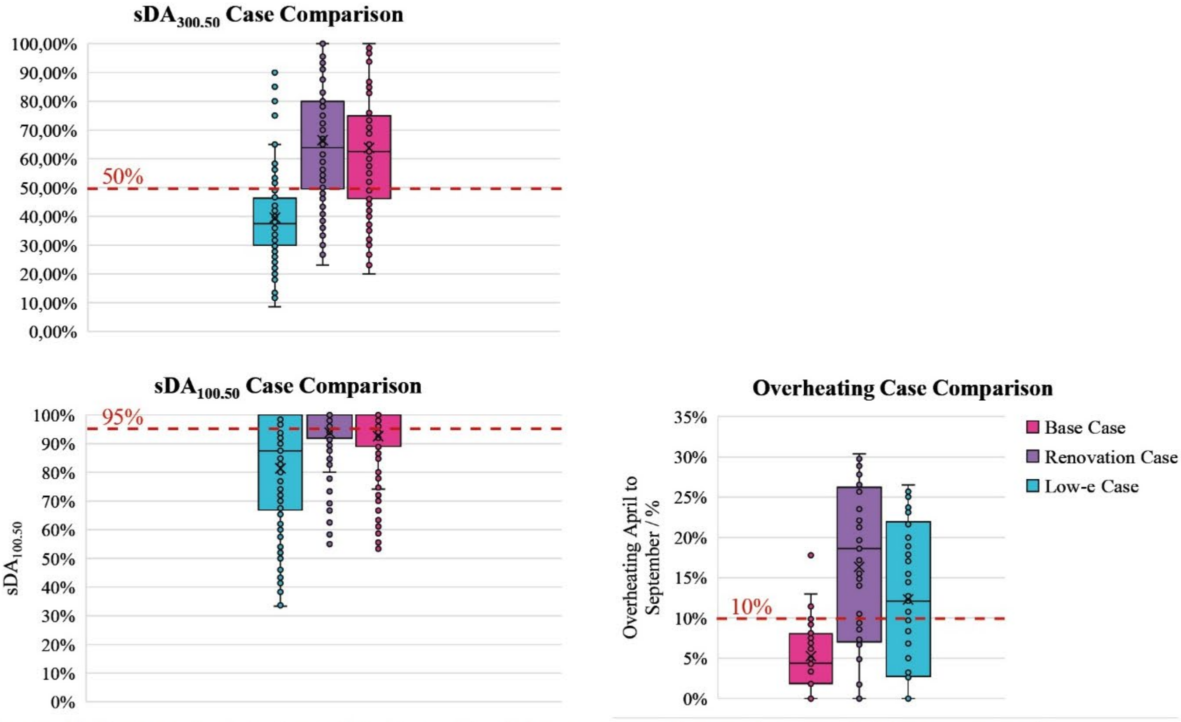
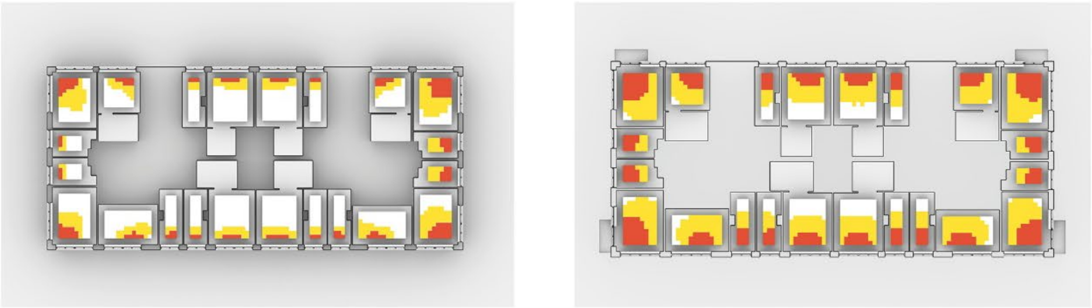


Figure 24 Comparison, in the form of box plots, of the sDA metrics, as well as overheating, of all three cases tested.

14. Postiljonen 15

Wollmar Yxkullsgatan 53, Stockholm. 1934. Multi-apartments building.

Base Case



Renovation Case

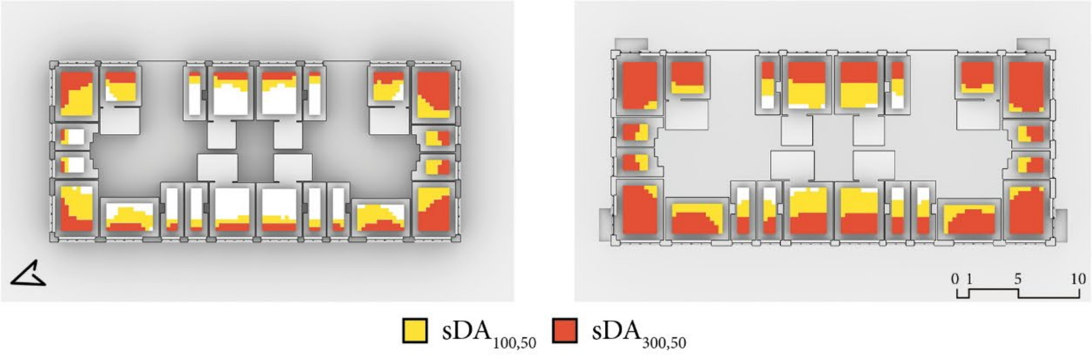


Figure 25 The sDA of all three cases tested. Left: ground floor, Right: top floor

Table 28 The EUI, EP_{pet} and energy class of all three cases tested.

	Base Case	Renovation Case	Low-e Case
EUI / kWh/m2/year	206,39	207,12	178,85
EPpet / kWh/m2/year	169,05	169,56	149,78
Energy class	F	F	F

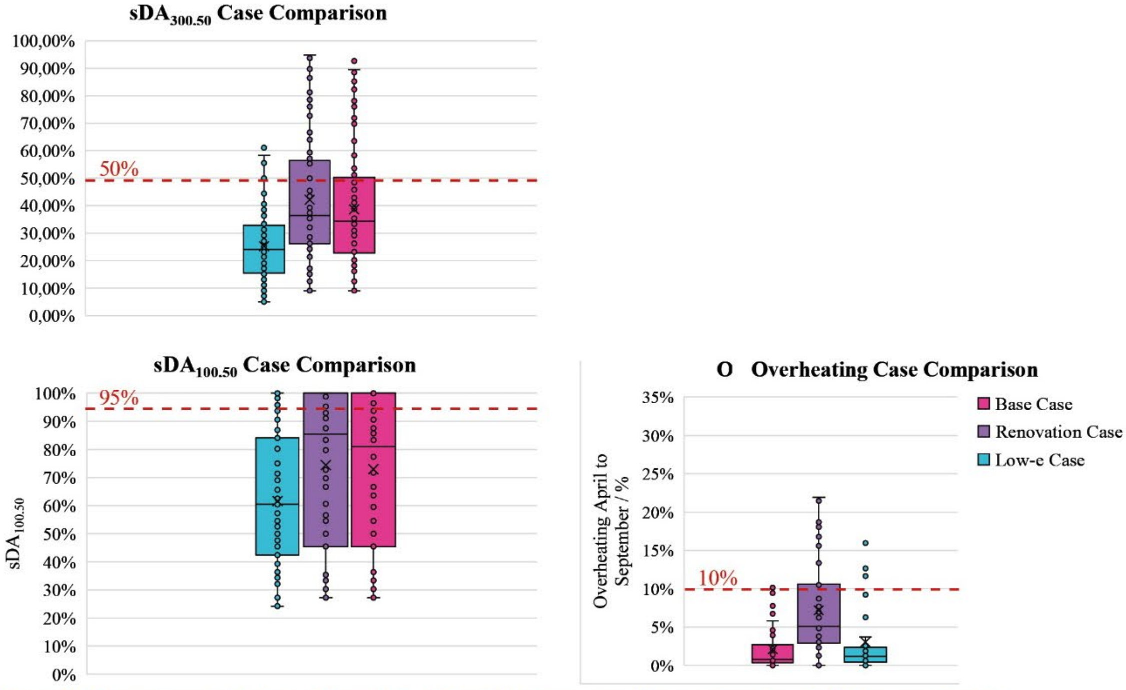
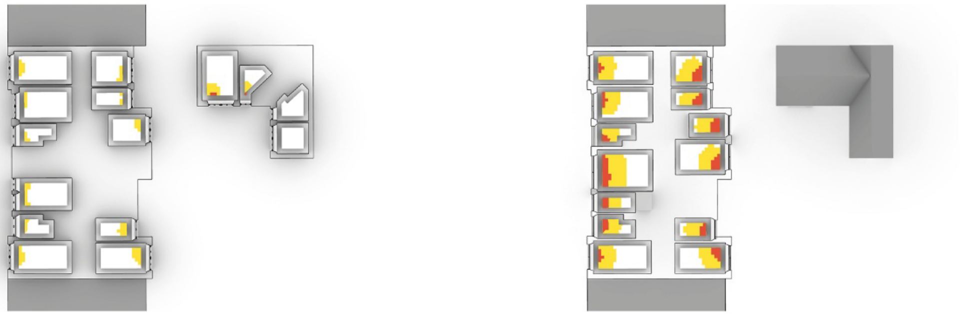


Figure 26 Comparison, in the form of box plots, of the sDA metrics, as well as overheating, of all three cases tested.

16. Pahl 8 Åsögatan 168, Stockholm. 1875. Large courtyard block.

Base Case



Renovation Case

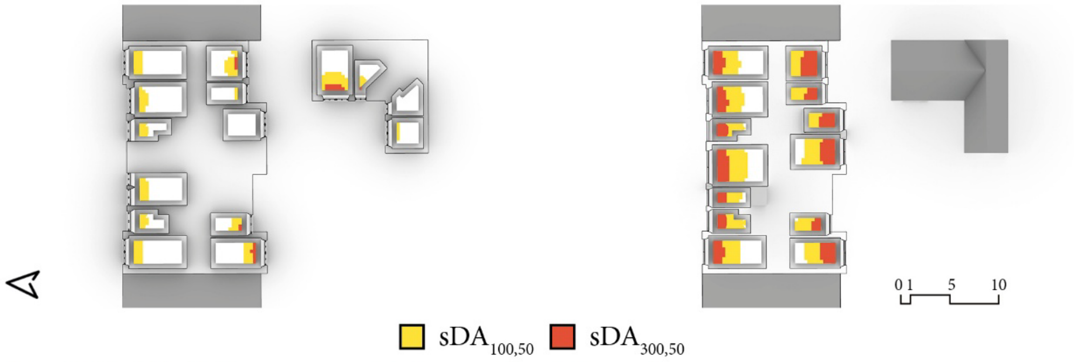


Figure 27 The sDA of all three cases tested. Left: ground floor, Right: top floor

Table 29 The EUI, EP_{pet} and energy class of all three cases tested.

	Base Case	Renovation Case	Low-e Case
EUI / kWh/m2/year	198,06	200,88	172,64
EPpet / kWh/m2/year	164,62	166,59	146,83
Energy class	F	F	F

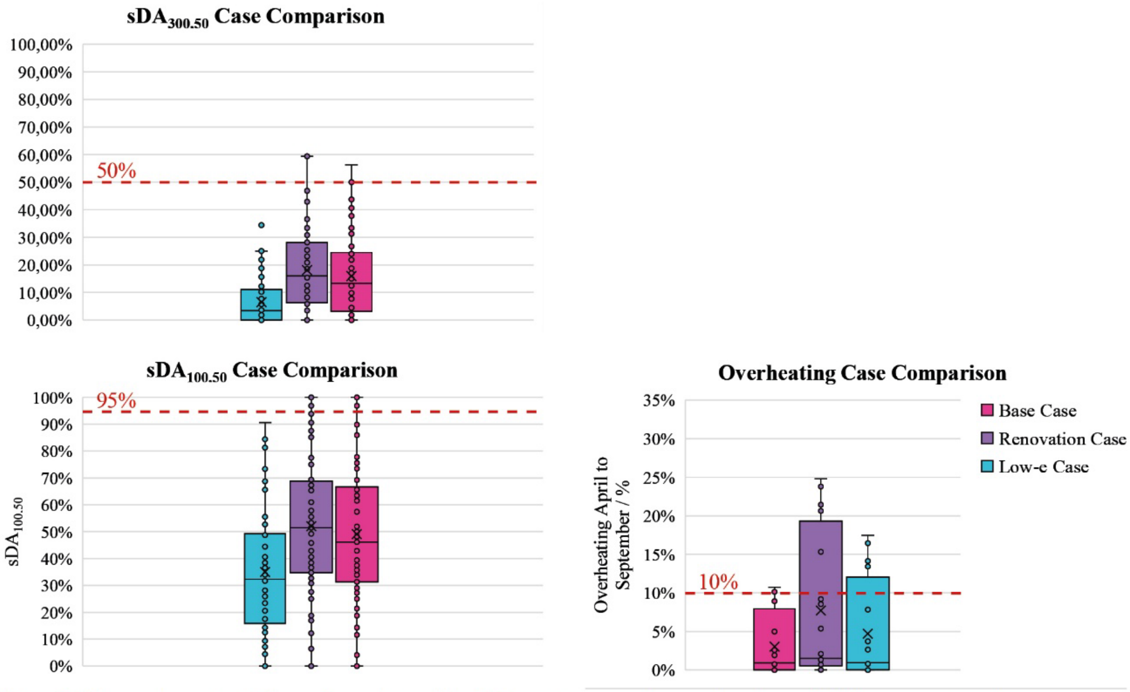
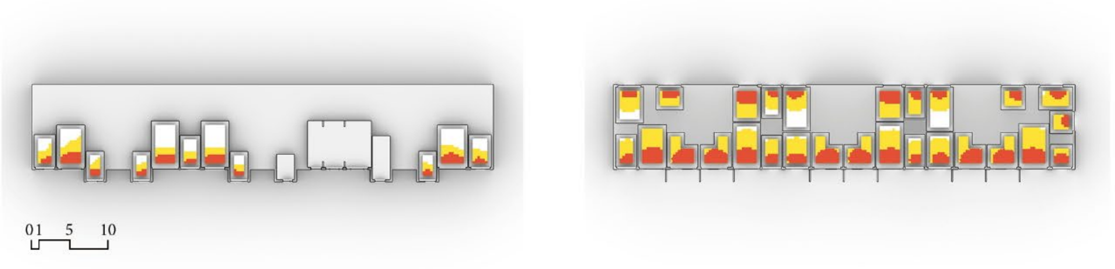


Figure 28 Comparison, in the form of box plots, of the sDA metrics, as well as overheating, of all three cases tested.

22. Branthomen 1:2

Brantholmsgränd 40-72, Stockholm. 1965. High-rise multi-apartment building.

Base Case



Renovation Case

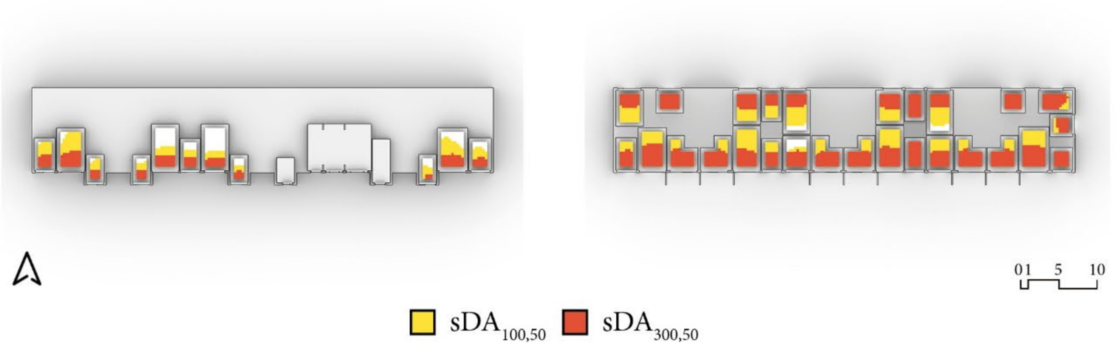


Figure 29 The sDA of all three cases tested. Left: ground floor, Right: top floor

Table 30 The EUI, EP_{pet} *and energy class of all three cases tested.*

	Base Case	**Renovation Case**	**Low-e Case**
EUI / kWh/m2/year	177,89	175,51	150,70
EPpet / kWh/m2/year	148,88	147,22	129,85
Energy class	F	F	E

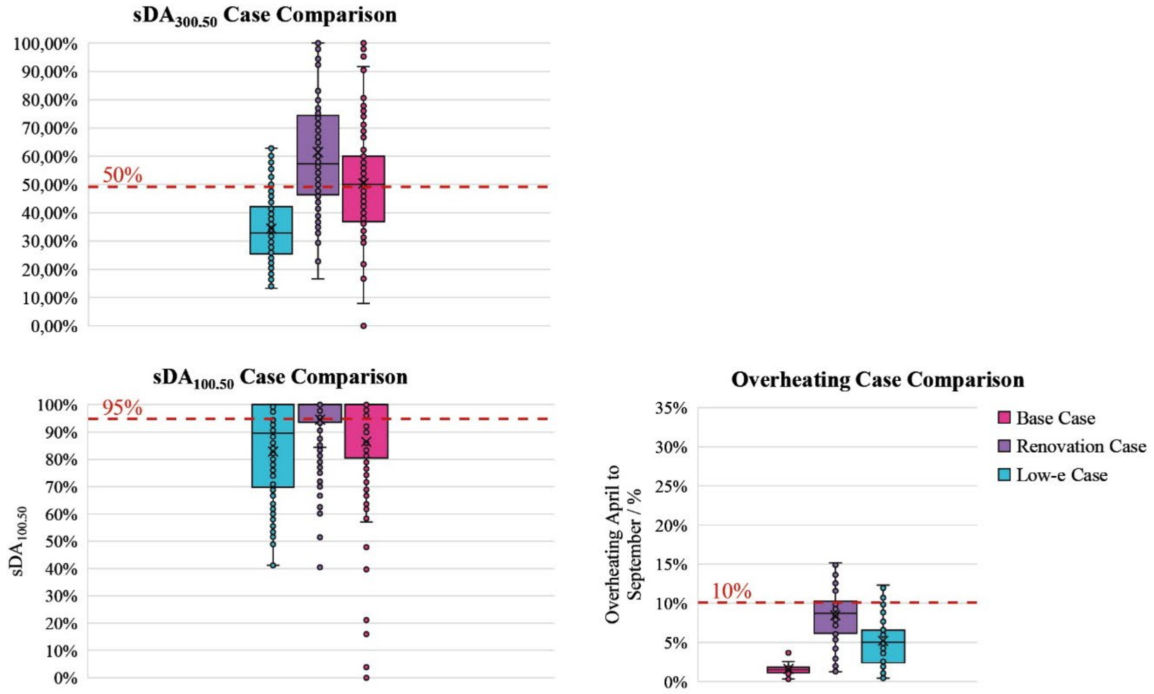


Figure 30 Comparison, in the form of box plots, of the sDA metrics, as well as overheating, of all three cases tested.

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