Low-Energy Solution for a High Temperature Problem

Assessing the Effectiveness of Passive and Low-Energy Cooling Strategies for Enhancing Heat Resilience in Residential Buildings in the Netherlands under Future Summer Climate Conditions

Final Thesis Report

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1. Research Framework

Abstract

As climate change increases the frequency and intensity of summer heat events, Dutch residential buildings face growing risks of overheating. In response, occupants are increasingly turning to energy-intensive air conditioning, further exacerbating climate impacts. This thesis investigates the effectiveness of passive and low-energy cooling strategies in enhancing thermal comfort and heat resilience in existing Dutch dwellings under future summer climate conditions. A mixed-methods approach was adopted, combining dynamic thermal simulations in Honeybee with resident questionnaires and expert interviews, applied to three typical housing types: detached, terraced, and apartment buildings.

The results show that the most effective strategies vary by room function. For living rooms, temperature-based ventilation, cross-ventilation, existing lightweight construction, and the addition of ceiling fans and solar shading proved most effective. For bedrooms, night ventilation combined with renovated construction and the same additional measures offered the best performance. Ceiling fans alone consistently outperformed both solar shading and green roofs in reducing thermal discomfort. Interviews and survey responses further revealed that residents and professionals continue to prioritize winter comfort over summer comfort, and value affordability, low energy use, environmental impact, ease of installation, and minimal maintenance—factors not captured by thermal metrics alone.

The findings suggest that, when occupancy hours are taken into account and strategies are applied in targeted combinations, passive and low-energy measures can significantly reduce overheating and dependence on air conditioning. When incorporated across multiple levels of the built environment, this could contribute to more sustainable and climate-resilient housing in the Netherlands.

Keywords

Thermal Comfort; Overheating; Safe indoor temperature standards; Low-energy cooling; Passive cooling; Ceiling fans

1. Introduction

Climate change and the Urban Heat Island (UHI) effect are increasingly driving global and urban temperatures upward, resulting in more frequent and intense heat events. Between 1980 and 2020, heatwaves accounted for over 85% of all weather- and climate-related deaths in Europe (EEA, 2024) and caused more annual fatalities worldwide than all other natural disasters combined (Luber et al., 2008). These extreme heat events also present health, social, environmental, energy, and economic risks (Meteorological Organization, 2023a; Zuo et al., 2015), especially for vulnerable groups such as children, the elderly, low-income households, and those who are socially disadvantaged, have chronic or mental health conditions (Keith et al., 2019; Zuo et al., 2015). As heat events become more frequent and severe, and urban populations continue to age and grow, making the built environment more heat-resilient becomes increasingly urgent.

In Europe, where people spend an estimated 90% of their time indoors (European Commission, 2003), ensuring thermally safe and comfortable indoor environments is essential. Yet, a large share of the building stock is poorly equipped to deal with these rising temperatures. Approximately 85% of European buildings were constructed before 2001 and are expected to remain in use until at least 2050; among these, an estimated 75% are energy inefficient and inadequately adapted to a warming climate (European Commission, 2020). Historically, buildings in Europe have been designed with a focus on heating—reflected in the average of 3200 heating degree days per year, compared to just 78 for cooling (Eurostat, 2024). However, demand is shifting. While heating needs have declined by 15% since 1979, cooling demand has nearly quadrupled, indicating a growing mismatch between current building design and future climatic realities. This trend has been confirmed for the Netherlands specifically by Gassert et al. (2021), who project a continued rise in cooling demand in the decades to come.

To meet the rising demand for indoor cooling, the adoption of air conditioning (AC) systems in the Netherlands is expected to increase significantly, with projections indicating that 40% of homeowners will own an AC unit by 2030 (Rovers, 2023; TNO, 2024). While air conditioning systems offer effective indoor cooling, they also increase energy demand, contribute to urban heat by expelling warm indoor air to the outside, and often rely on refrigerants that are potent greenhouse gases. The elevated electricity demand associated with AC use during extreme heat events—particularly at night—can also contribute to grid congestion, thereby increasing the risk of power system instability (DW Planet A, 2023; Zuo et al., 2015; TNO, 2024). Although numerous studies have recommended passive and low-energy strategies to mitigate indoor heat without significantly increasing energy demand—such as the cooling ladder proposed by Alders et al. (2025), the review of low-energy measures by Oropeza-Perez and Østergaard (2018), the proven effects of natural ventilation through window operation by Hamdy et al. (2017) and Chu (2023), and the CBE Berkeley guidelines demonstrating how ceiling fans reduce cooling loads by increasing airspeed (Raftery et al., 2023)—these approaches are not yet widely integrated or adopted in Dutch residential buildings.

The thesis begins with a literature review outlining current methods for assessing thermal comfort and highlighting gaps in the state-of-the-art to which this research contributes. Chapter 4 explores the perspectives and influence of key stakeholders in the built environment through semi-structured interviews and a questionnaire distributed to residents of Dutch homes. In Chapter 5, this qualitative insight informs the simulation of three common Dutch housing typologies—detached, terraced, and apartment dwellings—using Honeybee. A range of passive and low-energy cooling strategies is tested, and their performance is assessed using national indicators such as TO-hours, as well as through additional analyses that consider occupancy patterns, duration, and severity of overheating. Finally, Chapters 6 and 7 present the conclusions and reflection.

2. Literature Review

2.1 Thermal Comfort Assessment

There are several methods to define and assess thermal comfort and to evaluate the extent to which indoor and outdoor conditions can be deemed safe, without inducing heat stress or other adverse health effects related to extreme heat. This chapter first introduces two primary approaches to assessing thermal comfort: PMV/PPD model and the adaptive comfort model. Subsequently, the current Dutch guidelines for evaluating overheating and thermal comfort—namely the TO, GTO, ATG methods, and TO-juli—are discussed. Finally, thermal stress assessment models such as the PHS, SET*, and HI are compared with Dutch standards to determine which model is most appropriate for assessing thermal comfort and capturing variations in heat stress in typical Dutch residential buildings.

2.1.1 PMV / PPD Model

In 1970, Fanger introduced the Predicted Mean Vote (PMV) model, which predicts the average thermal sensation of a large group of users within a building under moderate conditions. Once the PMV of an indoor environment is known, the Predicted Percentage of Dissatisfied (PPD) indicates what proportion of users is expected to feel thermally uncomfortable.

The PMV/PPD model is static, meaning it assumes that the environmental conditions, as well as the activity levels and clothing insulation of occupants, remain constant during the calculation. According to Fanger, thermal sensation is influenced by six key factors (Fanger, 1970; RVO, 2018; Alders et al., 2024):

- Air Temperature (T_{air})
- Mean Radiant Temperature (MRT)
- Air Velocity (v_{air})
- Relative Humidity (RH)
- Metabolic Rate (M)
- Clothing Insulation (I_{clo})

PMV is expressed on a sensation scale from -3.0 (cold) to +3.0 (hot), with 0.0 being thermally neutral. Comfort standards generally allow PMV values to exceed the range of -0.5 to +0.5 for a limited number of hours per year. According to PPD, a space is considered thermally comfortable if no more than 10% of users are dissatisfied, that corrisponds with a PMV of ± 0.5. Figure 2.1 illustrates the relationship between PMV and PPD.

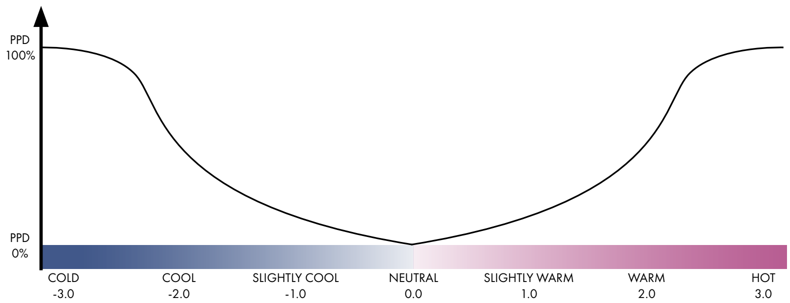


Figure 2.1 - PMV & PPD Levels, derived from RVO (2018) (Own Work, 2025)

Fanger's model is the basis of the international standard NEN-EN-ISO 7730, which is currently used in the Netherlands to assess thermal comfort in buildings. However, as noted in the ISSO publication by Alders et al. (2024), the PMV model is considered less suitable for naturally ventilated buildings during periods of high outdoor temperatures. This is because the model requires estimates for clothing insulation and activity levels for each moment in time—factors that are with air velocity more sensitive to changes than changes in temperature. A small error in estimating these personal parameters can result in PMV differences of up to 20%.

Fanger and Toftum later proposed an adjusted version of the model to improve its application in naturally ventilated buildings located in warm climates (Alders et al., 2024). While PMV is often described as a static model, it does allow for some level of adaptive behaviour—such as changes in clothing or activity level—

although such adaptations are difficult to estimate accurately across groups and time intervals. Since this study focuses on existing Dutch homes, which are mostly naturally ventilated, applying the PMV model correctly is crucial.

To better represent realistic conditions, this research uses behavioural assumptions inspired by the ISSO report Integraal Ontwerpen voor Zomercomfort by Alders et al. (2025). These assumptions are also tested against responses from Dutch residents through a questionnaire, in which participants were asked how they adapt their behaviour in response to heat when they are at home. The behavioural adaptations are grouped into the following categories:

- Personal adaptation, such as adjusting clothing and activity levels. Since the study focuses on homes, it is assumed that residents can wear light clothing and engage in low-activity tasks. These variables are defined per hour and per room and gathered from questionnaire responses.
- Technical/environmental adaptation, such as opening windows, adjusting shading devices, turning on fans, or using cooling systems. While many of these systems exist in homes, they are often used inconsistently or are not fully understood by occupants. Questionnaire responses are used to determine common behavioural patterns related to ventilation, shading, and fan use in the average Dutch household.
- Cultural/organizational adaptation, such as changes in dress codes or work schedules. These are less relevant for homes, where no formal restrictions typically apply to behaviour or attire.

2.1.2 Adaptive Model

Although the PMV model includes some aspects of adaptive behaviour, research has shown that people in naturally ventilated buildings are often comfortable within a wider range of temperatures. This is not only due to behavioural adjustments—something the PMV model can partly reflect—but also to psychological adaptation (de Dear & Brager, 1998). A key idea in the adaptive model is that people are not passive users of the indoor environment, as assumed by the PMV model, but actively shape their own thermal comfort. Therefore, the adaptive model suggests that thermal satisfaction depends on the match between the actual thermal conditions and an occupant's expectations of what those conditions should be in a given context.

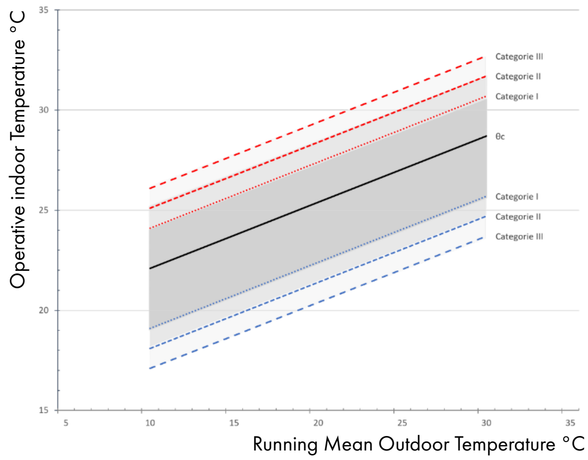
The adaptive comfort model estimates thermal comfort based on the outdoor climatic conditions experienced over the preceding days. At the core of this model is the Running Mean Outdoor Temperature (RMOT), a dynamic indicator that reflects the thermal history of the outdoor environment. The RMOT is calculated as a weighted average of daily mean outdoor temperatures (θ), with greater weight given to more recent days. This is done using an exponentially weighted moving average, defined by the following equation (Boerstra & Frei, 2024):

$$RMOT = \theta_{rm} = (1-\alpha)\,(\theta_{ed-1} + \alpha\theta_{ed-2} + \alpha^2\theta_{ed-3} + \ldots + \alpha_{n-1}\theta_{ed-n})$$

Based on the RMOT the comfort temperature is determined using the following linear relationship:

$$\theta_c = 0.33\theta_{rm} + 18.8$$

This formula is valid for outdoor running mean temperatures between 10°C and 30°C. The model then defines acceptable temperature ranges depending on the desired comfort category shown in Figure 2.2. These categories represent progressively wider comfort ranges, reflecting different expectations and sensitivities among building occupants (Alders et al., 2024). Category I is typically used in spaces occupied by vulnerable groups or where very high comfort is required, while Category III allows for greater variation and is more applicable in less critical settings. This method emphasizes the adaptability of human thermal perception and allows for greater energy efficiency by adjusting comfort expectations based on the recent outdoor climate, rather than enforcing a fixed indoor setpoint.



Category	Lower Limit θ_{min}	Upper Limit θ_{max}
I	$\theta_c - 3$	$\theta_c + 2$
II	$\theta_c - 4$	$\theta_c + 3$
III	$\theta_c - 5$	$\theta_c + 4$

Figure 2.2 - Temperature limits of Adaptive Comfort Model (Alders et al., 2024)

2.1.3 Natural Ventilated Buildings

According to the ISSO 74 publication, a distinction is made between a naturally ventilated building, referred to as an alpha space, and a mechanically controlled environment, known as a beta space (Alders et al., 2024). The conclusion is that the adaptive comfort model is suitable for alpha spaces, whereas the PMV model developed by Fanger should be applied to beta spaces. Figure 2.3 illustrates the criteria a building must meet to be classified as a truly naturally ventilated building.

A naturally ventilated building is characterized by the absence of strict clothing requirements, allowing occupants to adjust their clothing in response to the thermal environment. In addition, such buildings have a sufficient number of operable openings, enabling users to influence air movement, which in turn helps to shape their thermal expectations. Lastly, there is no noticeable presence of active cooling, as this would alter user expectations regarding thermal conditions. If any of these characteristics are not met, the space is classified as a beta space, for which the adaptive comfort model is no longer appropriate, and models such as PMV must be used instead.

For (existing) residential buildings where there are no clothing requirements, windows can be frequently opened, and no active cooling system is present, it can reasonably be assumed that the space qualifies as an alpha space. In such cases, the adaptive comfort model is the most appropriate method for assessing thermal comfort. The following sections outline the relevant Dutch regulatory methods based on both the PMV and adaptive models and evaluate which of these are most suitable for assessing thermal comfort in existing residential buildings.

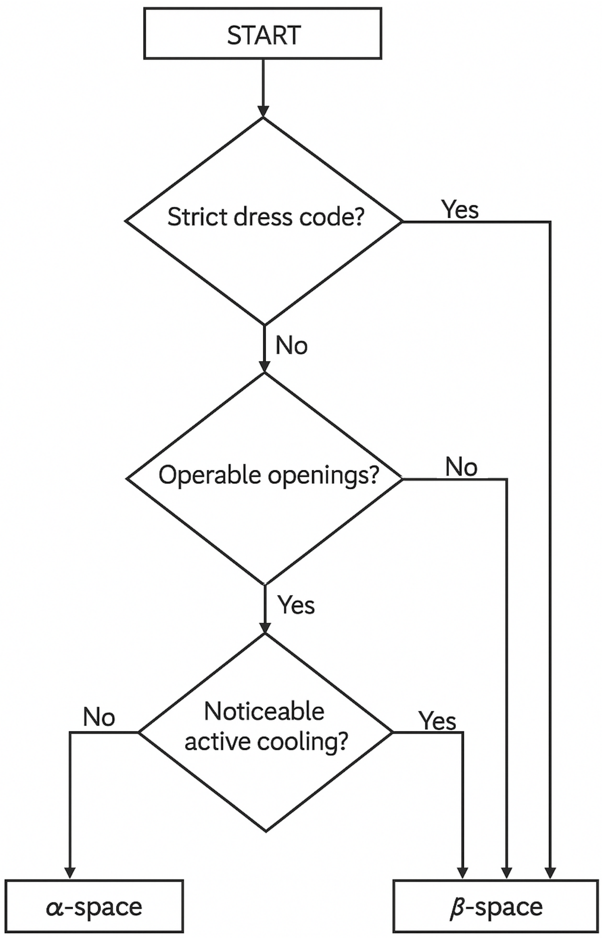


Figure 2.3 - Flowchart of when a Building is Natural Ventilated (α) or not (Alders et al., 2024)

2.2 Dutch Heat Resilience Assessment

In Dutch regulations, there are currently no mandatory requirements in place to limit overheating in existing residential buildings. However, there are assessment methods and guidelines available that allow for the evaluation of overheating risks, comparison between different dwellings or spaces within a building, and the assessment of the effectiveness of various cooling strategies. To provide a comprehensive overview, all relevant Dutch guidelines as outlined in ISSO 74 by Alders et al. (2024) are presented below.

2.2.1 TO-Hours

When simulations are applied to residential buildings, indoor environmental parameters—including air temperature, mean radiant temperature, air velocity, and relative humidity—can be generated on an hourly basis for the summer period. Combined with clothing insulation and metabolic rate values that in this case is obtained from the questionnaire, this data is used to evaluate thermal comfort using the TO-hours method. This approach applies threshold values based on the PMV/PPD model, assessing the extent to which indoor conditions exceed defined comfort and resilience limits.

The TO (Temperature Exceedance) method is based on the assumption that indoor air temperature equals mean radiant temperature (Tair = MRT), air velocity is 0.1 m/s, relative humidity is fixed at 50%, clothing insulation is 0.7, and the metabolic rate is 1.2. Under these conditions, a PMV of ±0.5 typically corresponds to indoor operative temperatures between 24.3°C and 27.2°C (Alders et al., 2024). To simplify the application of this model, standard temperature thresholds are used that assumes the factors as above. In residential buildings, the operative temperature should not exceed 25°C for more than 300 hours per year (corresponding to PMV ≥ +0.5, and temperatures above 28°C (corresponding to PMV ≥ +1.0) are allowed for a maximum of 100 hours per year (RVO, 2018). The total number of possible TO-hours is based on the summer period (June, July, and August), which includes 2,208 hours in total. This means that the worst-case theoretical scenario—where every hour of the summer exceeds PMV +0.5—would result in 2,208 TO-hours.

However, the TO-hours method does not account for the degree of exceedance. Whether the PMV limit is exceeded by 0.1 or 1.0 makes no difference in the calculation—both count as one full TO-hour. Additionally, the sequence of overheating is not reflected. A building with a few isolated overheating hours may receive the same total TO score as one with a continuous heat event, even though the impact on comfort or health may differ.

2.2.2 GTO-Hours

GTO-hours (Weighted Temperature Exceedance Hours) offer a more nuanced method for assessing thermal comfort by not only counting the number of hours in which a threshold value is exceeded, but also by incorporating the severity of the exceedance (RVO, 2018).

Similar to the TO-hours method, GTO is based on exceedance of a PMV value above +0.5. However, instead of treating all exceedance hours equally, GTO applies a weighting factor that corresponds to the level of discomfort, as defined by the PPD model. For example, one hour with a PMV that results in 10% dissatisfaction is equivalent to half an hour with 20% dissatisfaction. This allows GTO to better reflect the actual impact of thermal discomfort experienced by occupants. The GTO method uses the following formula to calculate the weighted contribution of each hour:

$$GTO = 0.47 + 0.22 \cdot PMV + 1.3 \cdot PMV^2 + 0.97 \cdot PMV^3 - 0.39 \cdot PMV^4$$

Only PMV values above +0.5 are considered in this method, and the calculation is capped at PMV = 2.5, since extreme PMV values (e.g., PMV > 2.0) are considered less reliable as thermal indices (like the TO-hour method). The preliminary target value for GTO in Dutch residential buildings is set at 450 GTO-hours per year for PMV > 0.5 (RVO, 2018). This threshold aim to prevent prolonged exposure to high levels of discomfort. During the simulation period covering June, July, and August—totalling 2,208 hours—the maximum theoretical number of GTO-hours that can be reached (if every hour records a PMV of 2.5) is 20,020 GTO-hours.

Although GTO-hours introduce a valuable improvement over the TO-hour method by acknowledging the intensity of overheating, this method—like TO—does not indicate the duration, sequence, or timing of the overheating periods. As a result, two buildings may have the same total GTO score while exhibiting very different overheating patterns and occupant experiences.

2.2.3 ATG - Method

The ATG method, which stands for Adaptive Temperature Guidelines, calculates the acceptable indoor temperature based on the Running Mean Outdoor Temperature (RMOT). It defines a range of indoor temperatures considered comfortable by incorporating behavioural adaptation, the psychological perception that occupants have some control over their thermal environment, and the physiological process of acclimatization. The specific calculation method is outlined in Section 2.1.2.

Although the ATG method is intended as a direct application of the adaptive comfort model—and is therefore theoretically suitable for existing dwellings classified as alpha spaces or naturally ventilated—it receives limited attention in ISSO publications. Moreover, for residential buildings, no maximum number of exceedance hours is defined in relation to this method. While the ATG provides a broader comfort range by considering adaptive actions, it does not account for situations in which such adaptive behaviours—such as opening windows—are not performed. As a result, thermal comfort may not be achieved even when the adaptive model suggests it should be.

2.2.4 TO-July

For newly constructed buildings or major renovations, compliance with the Dutch BENG standard (Nearly Energy-Neutral Buildings) is required. In line with the European Energy Performance of Buildings Directive (EPBD), BENG evaluates energy performance using three main criteria: maximum energy demand, maximum fossil energy use, and a minimum share of renewable energy (NEN, 2021). To assess overheating risk specifically, the accompanying technical guideline NTA 8800 includes the TO-july indicator, which evaluates indoor thermal conditions during the hottest month—July.

The TO-juli indicator is a design-based assessment tool used to evaluate the risk of indoor overheating in residential buildings, with specific attention to the building's orientation. It provides insight into potential temperature exceedance by taking into account factors such as window orientation and dimensions, shading elements (e.g., overhangs), construction characteristics (e.g., specific internal thermal mass), and thermal bridges, as well as the design of mechanical systems. This method calculates overheating risk by analyzing the relationship between the cooling demand for a specific orientation (Q_cooling_demand_orientation) and the total heat losses through transmission and ventilation ($H_{transmission} + H_{ventilation}$), multiplied by a time correction factor (t_{july}). This is expressed in the following formula below. A TO-july value greater than 2.0 indicates an unacceptable overheating risk in new residential buildings (TNO et al., 2022).

$$TO_{july} = Q_{cooling\_demand\_orientation} / (H_{transmission} + H_{ventialiont}) * t_{july})$$

TO_{july} number	Risk of overheating
0 - 2	No Risk
2 - 4	Medium to High Risk
> 4	High Risk

Unlike the TO-hour, GTO-hour, and ATG methods, the TO-july indicator does not incorporate comfort variables such as air temperature, mean radiant temperature (MRT), relative humidity, air velocity, clothing insulation, or metabolic rate. As a result, behavioral or technical improvements such as natural shading from vegetation, increased airspeed or changing clothing of the occupants are not reflected in the TO-july outcome. Moreover, the TO-july calculation is based on overheating risk at the whole-building level, whereas the TO and GTO methods allow for room-specific assessments, making it possible to prioritize thermal resilience in only several spaces.

2.3 Thermal Heat Stress Indicators

As discussed in Section 2.1.1, the optimal thermal comfort for occupants is typically reached when the Predicted Mean Vote (PMV) lies between -0.5 and +0.5, which corresponds to a maximum of 10% predicted dissatisfaction (PPD). In Dutch regulations, this comfort zone aligns approximately with a maximum of 300 TO-hours and 450 GTO-hours per year. However, these thresholds are based on comfort—not health. They do not indicate the critical physiological limits at which heat stress occurs or when health risks become significant. Therefore, it is essential to define the boundary at which indoor thermal conditions transition from discomfort to actual health hazards. To do so, this section compares several thermal heat stress models, based on the framework established by Cui et al. (2023). These include Predicted Heat Strain (PHS), Wet Bulb Globe Temperature (WBGT), Standard Effective Temperature (SET*), and the Heat Index (HI). Each of these models incorporates environmental and physiological parameters to evaluate heat stress, but they differ in application, assumptions, and suitability for residential indoor environments.

2.3.1 Predicted Heat Strain (PHS)

The PHS model is based on the human body's heat balance and shares input variables with the PMV model, such as air temperature, mean radiant temperature, air velocity, relative humidity, metabolic rate, and clothing insulation. However, its outcome differs: PHS evaluates physiological strain, including variables such as sweat rate, rectal temperature rise, and skin wetness, rather than subjective comfort.

PHS is particularly suited for occupational settings and aims to assess whether conditions are safe for extended exposure. For example, it assumes a maximum allowable rectal temperature of 38°C and a 5% water loss threshold (as a percentage of body weight) for up to 8 hours of exposure. Exceeding these limits can lead to physical health risks and must be avoided. Although PHS shares its input variables with the comfort models, its application to residential environments is limited. The model assumes high metabolic activity (1.7–6.8 MET), which is not representative of typical residential behavior. Therefore, it is not directly applicable for this study.

2.3.2 Wet Bulb Globe Temperature (WBGT)

The Wet Bulb Globe Temperature (WBGT) index assesses heat stress in outdoor environments with direct solar exposure, accounting for temperature, humidity, air velocity, and solar radiation. Due to its reliance on solar input, it is not suitable for evaluating indoor conditions and is therefore not used in this study.

2.3.3 Standard Effective Temperature (SET*)

The SET* model is a physiological model specifically for indoor environments. Like the PMV model, it uses variables such as air temperature, mean radiant temperature, air velocity, humidity, metabolic rate, and clothing insulation. However, it calculates an equivalent temperature based on a hypothetical isothermal environment with standardized conditions: air temperature = MRT, airspeed = 0.1 m/s, and RH = 50%. In this context, skin temperature and skin wetness are the boundary layers used to determine heat transfer from the core to the skin.

Research by Huizenga et al. (2024) indicates that for the U.S., a maximum SET* of 28°C is acceptable to avoid health risks in residential settings. This corresponds to an operative temperature of 30°C, which should not be exceeded for more than 120 hours or five consecutive days per year (Cui et al., 2023). Although these values are based on U.S. standards, they provide a globally applicable framework for evaluating indoor heat stress.

2.3.4 Heat Index (HI)

The Heat Index combines air temperature and humidity with physiological factors such as clothing and activity level to estimate the apparent temperature. While it also accounts for wind and solar radiation, its strong dependence on outdoor conditions makes it less suitable for evaluating indoor thermal comfort.

2.4 State of the Art

Among the various comfort assessment models and thermal heat stress indicators, two prominent studies have been conducted on Dutch dwellings—each employing a different method for calculating overheating. Both studies aim to assess the vulnerability of homes to climate change and to evaluate the effectiveness of various cooling strategies, forming the foundation upon which the present research builds.

2.4.1 Previous Studies on Overheating in Existing Dutch Residential Buildings

In a recent study by de Vries et al. (2024), the Amsterdam University of Applied Sciences collaborated with provinces, municipalities, housing associations, and other stakeholders to develop a factsheet aimed at improving summer comfort in Dutch residential buildings. The study assessed the performance of typical existing homes under current and future summer climate conditions by combining indoor temperature measurements with simulation modelling. The primary objective was to identify which interventions most effectively reduce the number of GTO-hours (Weighted Temperature Exceedance Hours) in bedrooms. Simulations were carried out for three common housing types—a portico apartment, a terraced house, and a corridor apartment—and evaluated four categories of measures: 1) the addition of solar shading, 2) varying levels of Urban Heat Island (UHI) intensity (0 °C, 3 °C, and 5 °C), 3) different ventilation behaviours (windows always closed, opened during transitional hours, night-time ventilation, and continuously opened), and 4) a range of insulation levels classified as poor (up to R2.5), moderate (R2.5–R3.5), and high (R4.5).

For the GTO calculations, the standardized assumptions listed in Table 2.1 were applied, using an hourly indoor temperature threshold of 26 °C to define exceedance. To support these simulation inputs, a survey of over 1,000 residents from Dutch housing associations was conducted, identifying four typical ventilation behaviour profiles regarding window operation. These profiles aligned with the simulation scenarios. The results indicated that night-time ventilation and continuous ventilation consistently with the use of solar shading led to the lowest GTO-hour totals across all housing types and intervention scenarios.

Additionally, the study explored the interaction between insulation performance and various ventilation and shading strategies. A key finding was that in poorly ventilated scenarios—such as "windows always closed" or "transitional ventilation"—higher insulation levels resulted in increased GTO-hours, indicating greater indoor heat retention. In contrast, in cases with sufficient night-time or continuous ventilation, improved insulation contributed to a reduction in GTO-hours, highlighting a synergistic effect between insulation and effective ventilation. In all scenarios, the addition of solar shading consistently lowered GTO-hours compared to unshaded conditions.

However, the study by de Vries et al. did not specify whether cross or single-sided ventilation was assumed, as airflow velocity was fixed at 0.1 m/s. This omission is significant, particularly in light of findings by Chu (2023), who demonstrated that cross ventilation can achieve ventilation rates up to 20 times higher than single-sided ventilation under the same outdoor airspeed and window opening area. Similar limitations apply to other assumptions in the study, such as equating air temperature with mean radiant temperature and fixing relative humidity at 50%. In reality, relative humidity in naturally ventilated Dutch dwellings is often closer to 70%, and these variables can vary significantly by room, scenario, and time of day. Such factors can substantially influence thermal comfort outcomes.

Despite the benefits of passive measures, the study also found that even the most effective combinations did not always reduce GTO-hour totals below the 450-hour threshold currently considered acceptable for all residential building types. In a follow-up interview, de Vries noted that the GTO-hour metric may not fully capture the thermal discomfort actually experienced by residents. A prior study by Hamdy et al. (2017) applied a different approach to assessing overheating in the Dutch housing stock. Their method was based on thermal comfort limits that reflect occupants' behavioural adaptability and the degree of control they can exert in different rooms—similar to the adaptive model. Moreover, the study calculated both the intensity and frequency of overheating in specific rooms during actual occupancy hours. This approach aimed to more accurately reflect how residents experience thermal conditions in each space and whether these conditions align with their comfort expectations.

The study by Hamdy et al. primarily examined which typical existing residential buildings in the Netherlands are best equipped to mitigate the impacts of global warming through different adaptive behavioural cooling strategies. The results showed that increasing ventilation consistently reduced overheating across all housing types. Notably, the greatest risk of overheating was observed in two contrasting dwelling types: detached houses with large glazed facades allowing substantial solar gains, and highly insulated apartments with limited exterior surface area and low heat transmission. Ventilative cooling and solar protection measures—such as external shading—were identified as the most effective passive adaptation strategies. However, the authors warned that if average outdoor temperatures rise by more than 3 °C, many homes may experience severe overheating. In such conditions, conventional adaptive measures—including natural ventilation, solar shading, lighter clothing, and reduced activity—may prove insufficient, making the integration of active cooling systems necessary to ensure thermal comfort.

2.4.2 Previous Study on Active and Passive Cooling Strategies

As a complement to the behavioural and simulation-based findings of de Vries et al. (2024), and the ranking of Dutch residential buildings based on overheating with adaptive cooling measures, the literature review by Oropeza-Perez and Østergaard (2018) offers a comparative analysis of various cooling strategies, evaluating their effectiveness, energy use, cost, and feasibility, while also identifying their suitability across different climates, building types, and budget levels.

Given the focus of this study on existing Dutch dwellings in a mild temperate climate with humid summers, only a subset of the cooling strategies reviewed by Oropeza-Perez and Østergaard (2018) is applicable. For instance, phase change materials (PCMs), while effective in lowering indoor temperatures, are costly and invasive to retrofit, making them impractical in this context. Likewise, changing façade colours may reduce solar gains in summer but is often restricted by aesthetic or regulatory constraints and may increase winter heating demand. By contrast, green roofs present a more viable passive solution, capable of reflecting 30–50% of solar radiation and acting as convective, evaporative, and thermal mass barriers, thereby contributing to reduced overheating.

Among all strategies, air conditioning provided the greatest cooling potential (up to 28 °C reduction), but with significant energy use (800–4000 W). At the other end, solar shading achieved only modest reductions (<1 °C) without energy input, though it proved more effective in studies by de Vries et al. (2024) and Hamdy et al. (2017). Ceiling fans emerged as a promising low-energy alternative, achieving up to 6 °C reduction in both reviewed and simulated results.

Although ceiling fans do not reduce air temperature directly, they significantly enhance perceived thermal comfort by increasing air movement. As described by Oropeza-Perez and Østergaard (2018) and Raftery et al. (2023), the airflow generated by fan blades boosts convective heat transfer and skin evaporation, enabling occupants to feel comfortable at higher indoor temperatures. Since this effect is perceptual, it is not reflected in temperature measurements alone. Therefore, the impact of ceiling fans is best evaluated using thermal comfort models that explicitly account for airspeed.

2.5 Contribution of this Research

Previous studies have assessed the overheating risk in typical Dutch residential buildings using passive and adaptive cooling strategies. This study builds upon these efforts by integrating behavioural and simulation-based insights from de Vries et al. (2024) and Hamdy et al. (2017), while also extending the analysis to include additional strategies identified in the reviews by Oropeza-Perez and Østergaard (2018) and Raftery et al. (2023). In doing so, this research aims to provide a comprehensive ranking of passive and low-energy cooling strategies for existing Dutch dwellings under future climate conditions.

Strategies considered include natural ventilation, solar shading, insulation improvements, glazing optimisation, green roof, ceiling fans, and occupant behaviour (e.g. lighter clothing, reduced activity). While these measures show promising results, several studies have indicated that with average outdoor temperatures rising beyond

3 °C, passive strategies may no longer be sufficient. Although air conditioning offers the highest cooling potential, it was deliberately excluded from this study due to its high energy consumption, use of greenhouse gases in refrigerants, and contribution to urban heat.

Given that most Dutch dwellings fall within the "alpha space" category—defined as spaces without mechanical cooling and where behavioural adaptation is possible—this study applies comfort models appropriate for naturally ventilated environments. While the adaptive thermal comfort model (e.g., ATG method) would, in theory, be most suitable for these buildings, it is only briefly addressed in Dutch guidelines and lacks clearly defined exceedance thresholds for use in residential settings. Moreover, it presumes occupants will consistently adapt their behaviour, which may not align with actual practice.

To evaluate thermal comfort exceedance more consistently, this study applies the TO-hour method, which is based on the simplified PMV/PPD model and is explicitly included in Dutch guideline ISSO 74. This model has assumed fixed indoor conditions: an air velocity of 0.1 m/s, relative humidity of 50%, a clothing insulation level of 0.7 clo, and a metabolic rate of 1.2 MET. It also assumes that air temperature equals mean radiant temperature. These simplifications make it possible to translate PMV thresholds directly into temperature limits—where a PMV of +0.5 corresponds to 26 °C and a PMV of +1.0 corresponds to 28 °C. According to ISSO 74, the acceptable exceedance durations are capped at 300 hours per year for PMV > +0.5 and 100 hours per year for PMV > +1.0 (Alders et al., 2024). These thresholds are therefore used as regulatory benchmarks in this study.

In comparison, the SET* model—defined in ASHRAE Standard 55 and explained in Section 2.1.3.3—follows a similar physiological logic but introduces more complex inputs, including skin temperature and moisture balance. It assumes slightly different baseline conditions: a lower metabolic rate (1.0 MET) and lighter clothing insulation (0.4 clo). Although more detailed in modelling the human heat balance, SET* yields thresholds that closely align with the PMV model. A SET* of 28 °C, for example, is considered equivalent to a PMV of +1.0 and is used as an upper comfort limit, with ASHRAE recommending a maximum of 120 SET* hours per year (Cui et al., 2023; Huizenga et al., 2024).

While TO/GTO and SET* differ in technical complexity, both use comparable thermal comfort thresholds, as shown in Table 2.1. Dutch guidelines are slightly more conservative than international standards, limiting PMV ≥ +1.0 to 100 hours per year, compared to the 120 SET* hours allowed by ASHRAE. Given this alignment and the direct connection of the TO-hour method to Dutch regulations, it was chosen as the primary assessment metric in this study. Although the GTO method accounts for the severity of overheating, it lacks a defined threshold for PMV > +1.0, reducing its suitability for compliance analysis. Similarly, while the SET* model offers a more detailed physiological approach, it is not widely used in Dutch residential research and is not included in national guidelines.

	Assumptions	Thresholds	Corresponding PMV	Max. Acceptable Exceedance
TO / GTO *(NEN-EN-ISO 7730)*	T_{air} = MRT v = 0.1 m/s RH = 50 % M = 1.2 I_{clo} = 0,7	$T_{operative}$ = 26 °C	PMV ≥ 0.5	TO = 300 hours GTO = 450 hours
		$T_{operative}$ = 28 °C	PMV ≥ 1.0	TO = 100 hours
SET* *(ASHRAE 55-2017)*	T_{air} = MRT v = 0.1 m/s RH = 50 % M = 1.0 I_{clo} = 0,4	$T_{operative}$ = 28 °C SET* = 27 °C	PMV ≥ 0.5	-
		$T_{operative}$ = 30 °C SET* = 28 °C	PMV ≥ 1.0	120 °C SET* - hours

Table 2.1 - (RVO, 2018; Huizenga et al., 2024)

To translate the theoretical insights on assessment methods, cooling strategies, behavioural aspects, and the influence of regulation and responsibility into practical applications, Chapter 4 presents a series of interviews and questionnaires with stakeholders from various levels of the built environment. Furthermore, in Chapter 5, the proposed TO-hour method is applied within a robust simulation framework to evaluate a comprehensive range of passive and low-energy cooling strategies. Together, these analyses provide a regulation-aligned and context-specific foundation for enhancing thermal resilience in existing Dutch dwellings. The resulting effectiveness rankings offer actionable guidance for prioritising interventions under future climate conditions.

3. Methodology

3. Methodology

3.1 Interviews and Questionnaire

To address the first sub-question, semi-structured interviews were conducted with stakeholders possessing expertise in thermal comfort, overheating in the Dutch context, building design, and policy implementation. Due to practical limitations—including availability, willingness to participate, and access through personal networks—a total of eleven professionals from diverse backgrounds were selected. The interviews explored key thematic areas relevant to the feasibility and real-world applicability of passive and low-energy cooling strategies, including: interpretations of thermal comfort; the role of regulations; preferences regarding the timing and spatial conditions for achieving thermal comfort; types of cooling strategies—with particular attention to air conditioning and ceiling fans; occupant behavior in relation to cooling strategies; and stakeholder responsibilities in implementation.

Interviewees from the design side were not required to have expert knowledge on overheating, as the focus was on whether such strategies are applied in practice. In some cases, a single interviewee represented the position of an entire sector; in such instances, findings were cross-validated against existing literature to ensure reliability. To compare expert perspectives with user experiences, a questionnaire was distributed among Dutch residents. This survey was distributed through personal networks and therefore limited to respondents reached via these channels. Any individual living in the Netherlands was eligible to participate, and the collected responses were considered representative for the purposes of this study. The detailed questions and results from the interviews and questionnaire are presented in Appendices 4.1 through 4.10.

3.2 Overall Evaluation of the Effectiveness of Cooling Strategies

The second part of this thesis focuses on evaluating and comparing the effectiveness of various cooling strategies. Figure 3.1 presents a diagram outlining all the relevant factors used in the effectiveness assessment, as well as their sources. In this study, effectiveness is measured and compared using the TO-hours method, which is further detailed in Chapter 2. Since this method is based on Fanger's Predicted Mean Vote (PMV) model, it requires six input variables: air temperature, mean radiant temperature, relative humidity, air velocity, clothing insulation, and metabolic rate.

This methodology section explains how the relevant input data were obtained for the selected residential case studies. The environmental parameters—air temperature, radiant temperature, relative humidity, and air speed—were derived from building simulations conducted in Honeybee. Additional airspeed values of ceiling fans were determined using the CBE Ceiling Fan Tool. Lastly, the values for clothing insulation and metabolic rate were obtained through responses to the questionnaire distributed among residents.

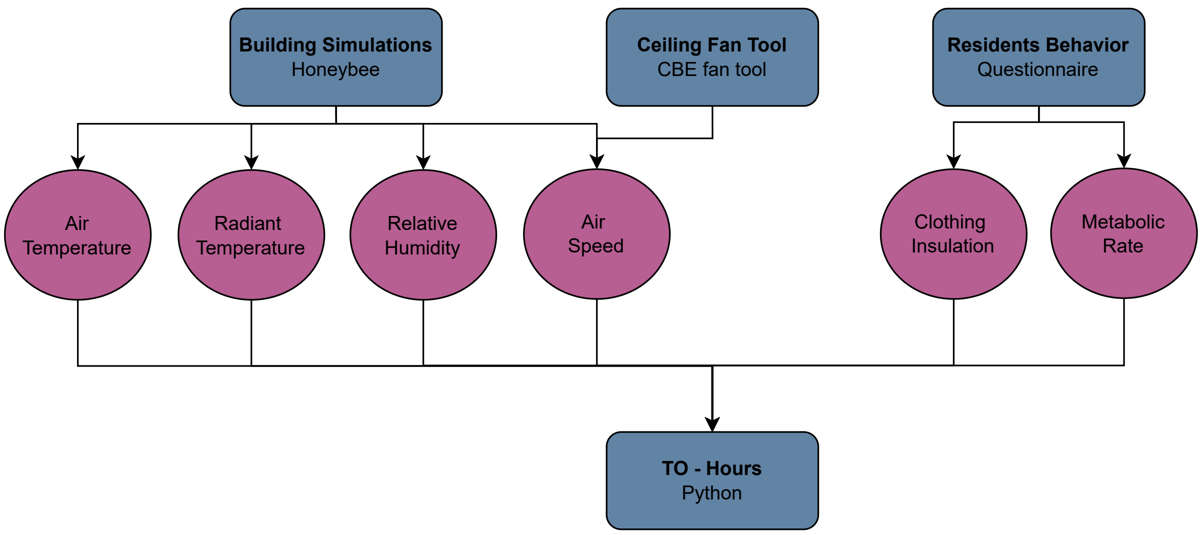


Figure 3.1 - Required data for TO calculations (own work, 2025)

3.2.1 Building Simulations

For the building simulation process, each selected case study requires specific input data to ensure that the most accurate and representative values are obtained for key environmental factors such as air temperature, mean radiant temperature, relative humidity, and air speed. The following section outlines all necessary input parameters and explains the choices made in this study to define these variables.

3.2.1.1 Climate and Location

For the building simulations conducted in this thesis, EnergyPlus Weather (EPW) files were used, as these are compatible with the Honeybee simulation tool. Since the study focuses on Dutch residential buildings, climate projections specific to the Netherlands were applied.

The Royal Netherlands Meteorological Institute (KNMI) provides detailed climate datasets based on over 120 years of hourly weather records, including temperature, relative humidity, wind speed, and solar radiation (Bessembinder et al., 2023). Using these datasets in combination with climate model projections, KNMI has developed future scenarios based on different greenhouse gas emission pathways: a high-emission scenario (H), which assumes continued emissions growth and results in a projected global temperature increase of 4.9 °C by 2100, and a low-emission scenario (L), which aligns with the Paris Agreement targets and limits the increase to 1.7 °C. These scenarios represent a broad range of potential future climate conditions in the Netherlands.

For this study, EPW weather files for De Bilt were obtained from Heiranipour et al. (2024), who generated future climate data for the years 2020, 2050, and 2080 using three downscaling techniques: CCWeatherGen (morphing method), Meteonorm (statistical method), and Regional Climate Models (RCM) using dynamic downscaling. All datasets were modelled under RCP 8.5, the highest-emission scenario, which corresponds to a radiative forcing of 8.5 W/m² by the end of the century (Machard et al., 2024).

This study focuses on the summer period (June, July, August), when overheating risks are highest. Among the three downscaling approaches, the CCWeatherGen files were selected. Although slightly warmer, they align most closely with KNMI's future climate projections. Figure 3.2 shows the hourly outdoor temperatures for June through August under the 2050 future scenario, compared to the 2020 baseline. As expected from the morphing method, the weather patterns remain consistent while average temperatures increase by approximately 2 °C—consistent with KNMI forecasts.

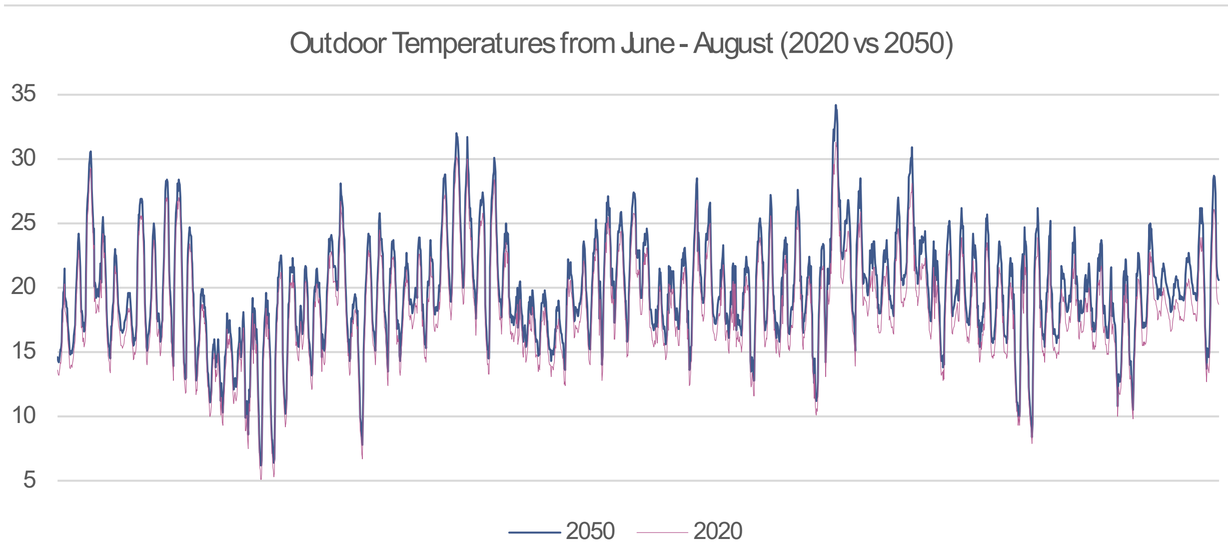


Figure 3.2 - Outdoor Temperatures from June - August in 2020 & 2050 based on Machard et al. (2024) (own work, 2025)

3.2.1.2 Building Performance Simulation Setup

To represent the Dutch housing stock through a limited number of simulations, this study adopts the categorization provided in the Voorbeeldwoningen 2022 Bestaande Bouw report published by the Dutch governmental agency (RVO, 2022). This document classifies approximately 8 million Dutch dwellings into categories based on building age, typology, and construction characteristics. It is specifically designed to serve as a representative framework for conducting energy performance analyses of residential buildings in the Netherlands. Three residential typologies were selected based on their largest representation within the national housing stock and are shown in Figure 3.3:

- Detached house, built before 1964 (418,000 homes, 5.6%)
- Terraced house (mid-row), built between 1975 and 1991 (573,000 homes, 7.7%)
- Apartment (stacked), built between 1965 and 1974 (209,000 homes, 2.8%)

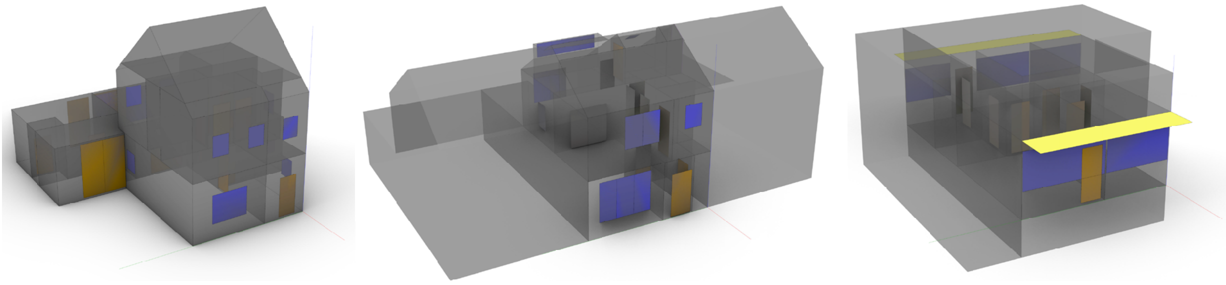


Figure 3.3 - Detached, Terraced and Apartment Residence in Simulation Software (Own work, 2025)

For each of the selected housing types, typical building dimensions, insulation levels, and system configurations were derived from the RVO report and are summarized in Table 3.1. These data informed the definition of the current (pre-renovation) construction scenario. For the renovated scenario, upgraded thermal values were applied based on RVO guidelines, incorporating improved insulation, glazing, and airtightness. Specifically, thermal resistances of R = 3.50 $m^2 \cdot K/W$ were used for floors and roofs, R = 1.70 $m^2 \cdot K/W$ for walls, and U-values of 1.40 $W/m^2 \cdot K$ for windows and doors.

Although the simulated buildings are generic and not tied to a specific location, a north–south orientation was applied in all cases to represent a worst-case scenario for overheating, given the high solar exposure on the south façade. Questionnaire responses further indicated that thermal comfort is most critical in the bedroom, followed by the living room. As a result, each building model was subdivided into multiple thermal zones, with the living room and one bedroom selected for detailed analysis of thermal resilience across different cooling strategies.

For the detached dwelling, the living room faces south and the bedroom is located on the upper floor facing north. In the terraced house, both the living room and bedroom face south, but are located on the ground and first floors, respectively. In the apartment, both spaces also face south but are situated on the same level, adjacent to each other. This setup allows the simulations to account for both orientation and vertical positioning within the building.

Housing type	Usable Area (m²)	Building Height (m)	Ground Floor Area (m²)	Closed Facade (m²)	Sloped / Flat Roof (m²)	Window / Door (m²)
Detached House up to 1964	153,28	9,00	89,59	131,12	84,42 / 29,31	28,36 / 8,04
			R 0,15	R 0,35	R 2,50 / R 0,85	U 1,80 / U 3,40
Terraced House 1975-1991	113,6	9,00	49,15	37,86	58,40 / 0,00	18,17 / 4,55
			R 0,52	R 1,30	R 1,30 / R 1,30	U 2,90 / U 3,40
Apartment 1965-1974	84,00	23,50	84,00	23,94	-	20,07 / 4,47
			R 0,17	R 0,43	-	U 2,90 / U 3,40

Table 3.1 - Construction by Building Type based on RVO report (2023) (Own work, 2025)

3.2.1.3 Cooling Strategies

Once the basic simulation setup has been established, the selection of cooling strategies to be implemented in the simulation model can be made. These strategies are applied to assess their impact on indoor air temperature, mean radiant temperature, relative humidity, and airspeed within each selected thermal zone—parameters that will later be used for evaluating cooling effectiveness. The cooling strategies were chosen based on the review by Oropeza-Perez and Østergaard (2018) and the "Cooling Ladder" from the Dutch OSKA declaration, which ranks cooling measures by their sustainability and suitability for the Dutch climate. This prioritization framework is illustrated in Figure 3.4 (Duurzaam Gebouw, 2022; Alders et al., 2025).

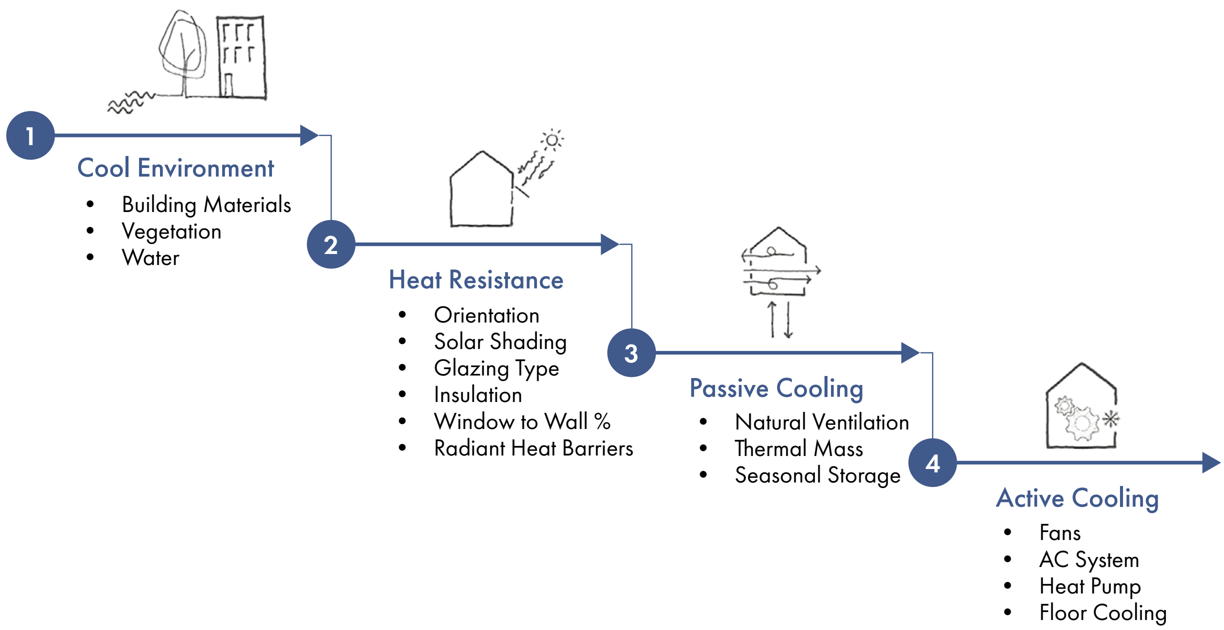


Figure 3.4 - Cooling Ladder derived from Duurzaam Gebouw (2022) and Alders et al. (2025) (Own Work, 2025)

1) Cool environment: The first level of the cooling ladder focuses on reducing the ambient temperature around the building. This includes measures such as planting trees for shading, integrating greenery, and using water elements to cool the surroundings. These strategies help reduce outdoor temperatures, lower heat transmission into the building, and mitigate the Urban Heat Island effect. Although green roofs are typically classified under heat resistance, they also provide evaporative cooling to the surrounding environment. In this study, a green sedum roof is applied for its lightweight construction, making it suitable for existing buildings and easier to implement and maintain.

2) Heat Resistance: The second level involves designing the building envelope to resist heat gain. Measures include optimizing window-to-wall ratios, building orientation, and passive systems such as thermal insulation, reflective glazing, and solar shading. In this study, both solar shading and green roofs (used here as radiant heat barriers) are applied. A tilted awning system was chosen for shading, as it minimally obstructs daylight, outward views, and airflow—factors that, according to questionnaire responses (15%, 22%, and 23% of participants, respectively), influence willingness to adopt such measures. Existing and improved insulation and glazing values (based on R-values and double glazing) are included in the simulation. Elements such as fixed shading (e.g., overhangs), orientation, and window-to-wall ratios are considered fixed for existing buildings and are therefore not modified for this study.

3) Passive Cooling: Passive cooling strategies aim to reduce indoor heat through natural, non-mechanical means. Core methods include single-sided ventilation and cross ventilation, both of which rely on user behavior to be effective. In this study, two occupant-driven ventilation schedules are examined: night ventilation, where windows are opened between 21:00 and 07:00, and temperature-based ventilation, where windows are kept open only when outdoor temperatures range between 15°C and 27°C. Both single-sided and cross ventilation strategies are simulated using each of these behavioral schedules to assess their comparative

effectiveness in enhancing thermal comfort. Although Aquifer Thermal Energy Storage (WKO) has proven effective in the Dutch context, it is not included in this study due to high investment costs and the invasive nature of retrofitting. Thermal mass is also excluded as the existing buildings already contain their respective thermal storage capacities, which remain unchanged across scenarios. While green roofs with thick substrate layers could contribute thermal mass, the sedum roof used in this study has a 4 mm layer, rendering its mass negligible.

4) Active Cooling: If the above strategies are insufficient, active cooling is introduced as the final step. This could include radiant floor cooling, heat pumps, air conditioning, and electric fans. In this study, ceiling fans are also assessed as a standalone measure to examine how increased air velocity can support thermal comfort and heat resilience—without the high energy demand of systems like air conditioners. Note that the effectiveness of fans is based solely on their impact on human thermal perception, not on their ability to change indoor climate conditions.

3.2.1.4 Workflow of Building Simulations

Once all input parameters have been gathered as described above, they can be entered into the building simulation model. Figure 3.5 presents a flowchart outlining the workflow used to set up the building energy simulations, which were conducted using Rhino 7, Grasshopper, and the Honeybee plugin. The simulations yield hourly data for air temperature, mean radiant temperature, relative humidity, and airspeed for each room within the case study buildings.

The process begins with the creation of simplified room volumes in Rhino, based on typologies from the RVO research report (RVO, 2022). These volumes are then imported into Grasshopper and defined as Honeybee Rooms for simulation purposes. At this stage, users may choose to model the building as a single thermal zone, divide it by floor levels, or represent each room as a distinct simulation zone. In this study, all rooms were modeled individually in order to capture temperature differences across building heights and to better represent the effects of natural ventilation and internal zoning on thermal performance.

In Honeybee, the defined Rooms are analyzed for matching surfaces (faces). When adjacent Rooms share common boundaries—such as walls, floors, or ceilings—Honeybee automatically detects these intersections and assigns appropriate adjacency properties. This ensures that thermal interactions between zones are accurately represented and prevents construction layers from being applied twice to the same surface.

Next, window surfaces are added in Rhino to the exterior faces of each Room and translated into Honeybee apertures. These apertures can be defined as operable windows, depending on the natural ventilation strategy applied—either single-sided or cross ventilation. In the single-sided ventilation scenario, the room is modeled with a window opening to the exterior, while the internal door remains closed, limiting airflow to a single façade. In contrast, the cross-ventilation scenario requires openings on opposite sides of the room to create a pressure differential and enhance airflow. In this case, windows are opened on both sides, and the interior door is modeled as an air wall, allowing direct airflow and heat transfer between adjacent rooms where windows are also open. For each ventilation type, specific opening schedules and opening fractions are applied, informed by occupant behavior from the questionnaire and the type of construction. Two behavioral schedules are used:

- Night ventilation, where windows are opened from 21:00 to 07:00 based on occupancy patterns reported in the questionnaire.
- Temperature-based ventilation, where windows remain open only when outdoor temperatures fall within the 15–27 °C range. This reflects the upper and lower thermal comfort threshold reported by respondents, under the assumption that windows would be closed once outdoor temperatures exceed 27 °C to prevent more heat gain.

Following this, shading elements can be added to the exterior of the windows. These may include external shading devices, overhangs, or adjacent buildings that obstruct solar radiation. For each shading element, properties such as solar reflectance and the fraction of window obstruction can be specified. The construction details of each building component are then applied, distinguishing between current and renovated constructions. These include thermal resistance values (R-values), thermal mass, and the presence of radiant barriers at the exterior of the building.

In the next step, program data are assigned to each Room. This includes the number of occupants per time step, infiltration rates (expressed as façade leakage), and mechanical ventilation rates if active systems are present. For this study, two occupants are assigned to the living room between 07:00–09:00 and 18:00–21:00. However, based on questionnaire data, this is likely an overestimation, as 90% of respondents reported being at home primarily between 20:00 and 08:00. For the bedroom, one person is assumed to be present from 21:00 to 07:00, also aligned with the questionnaire results. Infiltration values are set uniformly across rooms. For the current construction scenario, an infiltration rate of 0.0004 m^3/s per m^2 of façade surface is applied, while the renovated construction assumes a reduced leakage rate of 0.0001 m^3/s per m^2, consistent with construction benchmarks from RVO (RVO, 2022). Additional schedules for lighting, electric appliances, gas equipment, and hot water use can also be included in this component. However, although these factors do contribute to internal heat gains, their impact is considered negligible within the context of this residential study.

Then, depending on the scenario, the user chooses whether the rooms are conditioned. If so, a custom HVAC system can be assigned—such as an air conditioner or floor cooling—using the IronBug plugin. If the rooms are unconditioned, they are instead connected to an airflow network that models natural air exchange.

Finally, the selected future weather file (EPW) is applied, and the model is executed in Honeybee. This generates room-specific simulation outputs on an hourly basis, including air temperature, mean radiant temperature, relative humidity, and air velocity at the window surface. The results are exported as structured Excel files and, together with data from the questionnaire, supplementary calculations, and the CBE Thermal Comfort Fan Tool, are used to assess the effectiveness.

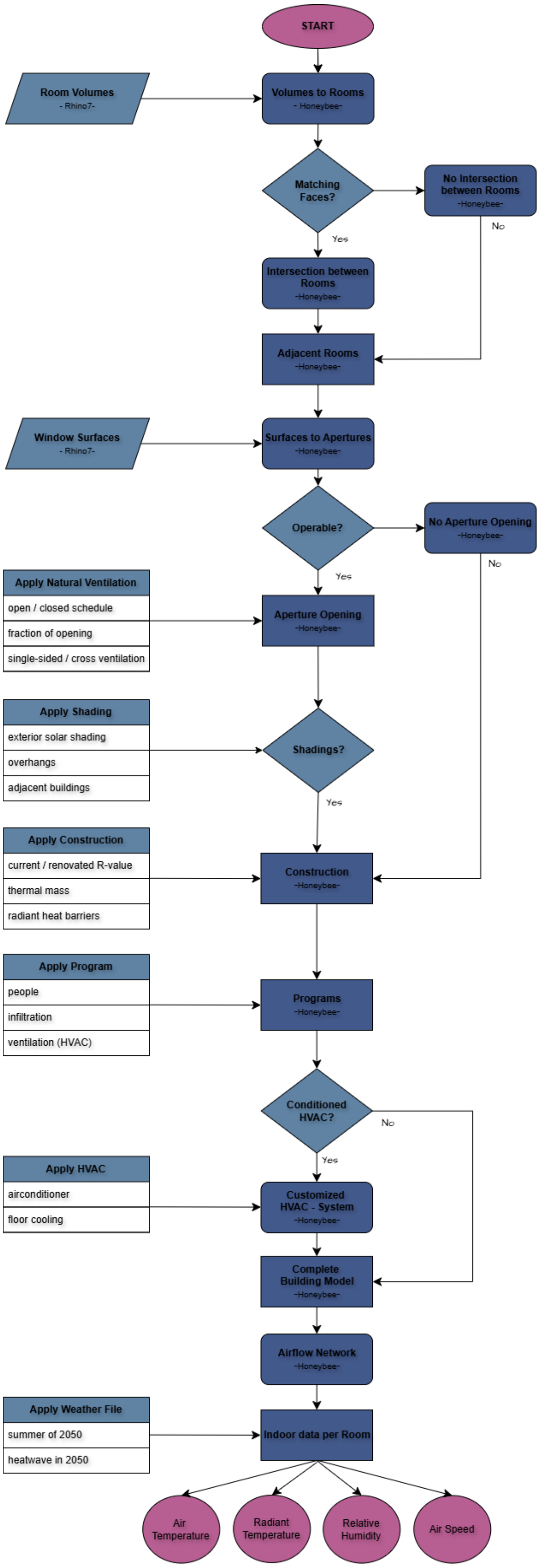


Figure 3.5 - Set up the building simulations (Own work, 2025)

3.2.2 Air Speed of Natural Ventilation and Ceiling Fans

After obtaining the airspeed at the window surface from the Honeybee building simulations, the average indoor airspeed within each room was calculated using equations from Chu (2023), which estimate volumetric airflow for different natural ventilation types.

For single-sided ventilation, the airflow Q (m^3/ s) was calculated using the formula, where $v_{,wind}$ is the airspeed at the window surface and A_{window} is the area of the window;

$$Q = 0{,}025 * v_{,wind} * A_{window}$$

For cross ventilation, the formula applied was, using the same variables as above, with a discharge coefficient Cd = 0.35 to reflect wind flow that is diagonal to the south façade:

$$Q = Cd * A_{window} * v_{,wind}$$

The resulting volumetric airflow values were then divided by the vertical cross-sectional area of the room to derive hourly average airspeed values. However, as some of these calculated values were lower than 0.1 m/s—below the threshold of perceptible airflow—all values below 0.1 m/s were standardized to 0.1 m/s for use in the thermal comfort and resilience calculations.

To incorporate ceiling fans into the simulation scenarios, the CBE Fan Tool developed by Raftery (2019) was used. This tool allows users to input room dimensions and select a suitable fan type based on spatial constraints. The selected fan models were validated against products commonly available in the Dutch market to ensure realistic applicability. The selection of a fan was primarily based on its diameter, to ensure it would fit within the space, and its ability to generate sufficient average airspeed, as indicated by the CBE tool. Given that the living rooms and bedrooms across all three dwelling types had similar dimensions, the same ceiling fan model was applied in each case: a fan with a 1.52-meter diameter, producing an average airspeed of 1.16 m/s. In scenarios involving fans, this airspeed was added to the natural ventilation baseline, allowing the model to account for the combined effects of passive and mechanical air movement in the calculations.

3.2.3 Residents Behavior

In the questionnaire distributed to 66 individuals of varying backgrounds, ages, and housing types, two questions focused on thermal behavior: the typical clothing worn on a warm summer day at home, and the types of activities carried out under such conditions. In previous studies, these values are often estimated. For example, SET* calculations commonly assume an average clothing insulation of 0.4 CLO and a metabolic rate of 1.0 MET (Huizenga et al., 2024), while for TO/GTO calculations by RVO (2018), values of 0.7 CLO and 1.2 MET are used.

Although these estimates aim to represent large population averages, the questionnaire results indicate that people at home tend to wear significantly lighter clothing and engage in the same relaxed activities. As a result, a clothing insulation value between 0.25–0.30 CLO and a metabolic rate of approximately 1.1 MET during the day were considered more realistic for this study. Furthermore, these values are not appropriate for modeling bedrooms, where the metabolic rate drops to around 0.7 MET during sleep, and the combined insulation from the bed, sheet, and sleepwear results in a value of approximately 1.5 CLO (Zaki et al., 2021).

3.3 Heat Resilience Indicators

Once all six thermal comfort parameters are gathered for both the bedroom and living room across the three residential building types, the data—exported as CSV files—serve as input for the thermal comfort calculations. The choice to use the PMV model, with threshold values of 0.5 and 1.0 in accordance with Dutch standards, is further justified in Chapter 2. These calculations are performed using the pmv_ppd function from the pythermalcomfort.models Python library. The output includes the number of hours during which PMV exceeds 0.5, indicating thermal discomfort, as well as hours exceeding PMV > 1.0, which are of particular relevance to this study due to their potential health implications and connection to the concept of thermal resilience.

4. Results of Interviews and Questionnaire

4. Results of Interviews and Questionnaire

The study by de Vries et al. (2024) revealed that residents may hold differing perspectives on the effectiveness of cooling strategies for their homes. Building on this insight, this chapter investigates the question: *What are the perspectives of stakeholders from various sectors of the built environment regarding the implementation and perceived effectiveness of cooling strategies for existing residential buildings?*

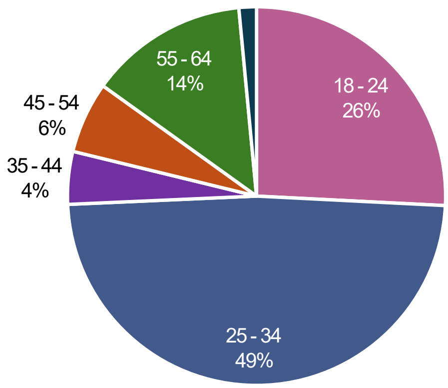
To address this question, interviews were conducted with key stakeholders, and a complementary questionnaire was distributed to residents of Dutch dwellings. This approach provides a broader understanding of stakeholder perspectives on thermal comfort, regulation, timing and location of cooling, cooling strategies, the role of occupant behavior, and perceptions of responsibility for implementing interventions.

By gathering diverse viewpoints on these topics, this chapter critically reflects on the practical effectiveness of cooling strategies—as evaluated by TO-hours in Chapter 2—and explores what additional factors must be considered for a more accurate and holistic assessment.

The following stakeholders were interviewed for this part of the study:

- Technical Specialist of ISSO
- Architect
- Physiologist
- Association of Housing Corporations
- Housing Corporation (2 people)
- Technical Installations Advisor
- Building Physics Consultant
- Froukje de Vries from "Hitte in de Woning" report
- Intereg (2 people)

In parallel, a resident questionnaire was conducted to complement the expert interviews, gathering responses from 66 individuals representing a broad range of age groups (Figure 4.1, left). The gender distribution was nearly equal, and most participants (95%) reported being in good to excellent health. Additionally, a diverse mix of housing types was captured in the sample, ensuring that perspectives across various residential contexts were reflected (Figure 4.1, right).



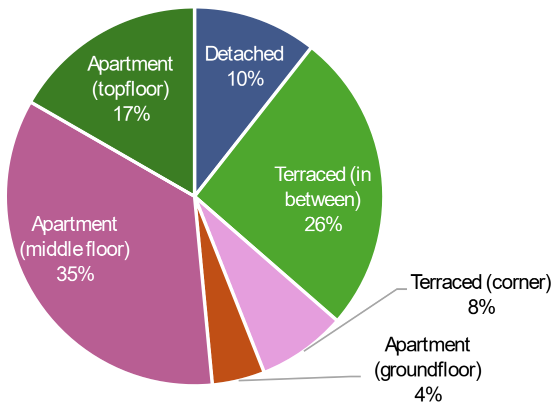


Figure 4.1 - Age (left) and Housing Type (right) of Respondents (own work, 2025)

Each topic in this chapter is introduced by summarizing the responses of the interviewed stakeholders, with anonymized transcripts provided in Appendices 4.1–4.7. This is followed by an analysis of perspectives from the resident questionnaire, included in Appendices 4.8-4.10. These results are primarily compared to the findings from two large-scale questionnaires conducted by de Vries et al. (2024), which together represent responses from over 2,000 participants collected over a two-year period.

4.1 Interpretation of Thermal Comfort

In the literature review of Chapter 2, various approaches to measuring thermal comfort were discussed, along with an explanation of how Dutch regulatory standards apply these models. What emerges as particularly interesting is how different stakeholders interpret thermal comfort, how they integrate it into their design processes, and what limits they—along with residents—identify in terms of heat resilience for residential buildings.

- Interview

Both the physiologist and the Technical Specialist of ISSO emphasized that thermal comfort must be understood as a complex interaction between six key factors: air temperature, mean radiant temperature, relative humidity, air velocity, clothing insulation, and metabolic rate. These variables are further influenced by a person's health, level of control over the environment, and the broader context in which they live.

While the PMV model is designed to estimate the average thermal sensation of a large group of people, and indicators such as TO- and GTO-hours are built upon its thresholds to assess overheating risk, the physiologist offered a more nuanced view of human comfort limits. As they explained:

"In fact, research suggests that occasional exposure to mild heat or cold—beyond the standard thermal comfort zone—can have positive health effects, indicating that remaining strictly within a thermoneutral range is not always necessary or beneficial."

This is supported by the findings of van Marken Lichtenbelt et al. (2022), who demonstrated that mild heat acclimation leads to physiological adaptations such as increased sweat production, enhanced skin blood flow, and reductions in heart rate, blood pressure, and core body temperature. Additionally, improvements in glucose metabolism were observed, including lower blood glucose levels and enhanced insulin sensitivity following passive exposure to mild heat.

In contrast, design-oriented professionals, such as the Technical Installations Advisor, Building Physics Consultant, and Architect, are generally not familiar with all six PMV variables and do not explicitly apply them when designing HVAC systems or passive cooling strategies. Instead, they rely on practical thresholds, such as maintaining 24.5 °C in summer or balancing air and radiant temperatures for overall comfort. The interviewed architect, for example, depends on consultants for thermal calculations and primarily influences the design through spatial orientation and the use of natural shading, such as trees.

Lastly, both the Housing Corporation and the Association of Housing Corporations confirmed that the topic of summer comfort and overheating resilience has only recently gained attention. As a result, the formulation of performance standards and intervention strategies is currently driven largely by tenant feedback, rather than by predefined technical criteria or regulatory requirements.

- Questionnaire

Although various models exist to assess thermal comfort at the group level, it remains a highly individual experience. In this study, respondents were asked to indicate the maximum indoor temperature they considered acceptable before taking action to cool their environment (Figure 4.2). Notably, 39% preferred a maximum temperature between 21–23 °C, while 32% accepted 24–26 °C. Compared to de Vries et al. (2024)—where only 17% preferred 21–23 °C and 63% opted for 24–26 °C—these results indicate a stronger preference for lower indoor temperatures.

When respondents were unable to sufficiently cool their homes, 94% reported poorer sleep, 61% had difficulty concentrating, 50% felt more fatigued, and 49% experienced excessive sweating (Appendix 4.9).

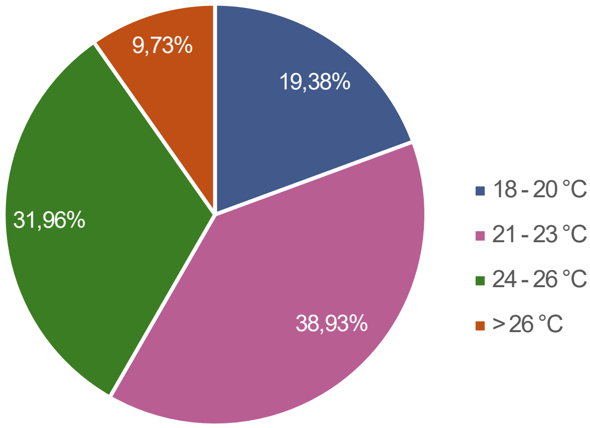


Figure 4.2 - Maximum Comfortable Indoor Temperature (own work, 2025)

Additionally, in the study by de Vries, 19% of participants preferred temperatures below 21 °C specifically for the bedroom. Interestingly, although thermal comfort was frequently mentioned as a key function of cooling technologies, only 56% of respondents selected it among their top three priorities. Instead, low cost, low energy consumption, and environmental friendliness were most frequently identified as the main selection criteria for cooling strategies, as further elaborated in Section 4.4.

4.2 Role of Regulation

In the Netherlands, the TO-juli standard is the primary regulatory tool for assessing overheating risk in new residential buildings. However, there are currently no legally binding standards for evaluating thermal comfort in existing dwellings (Alders et al., 2024). As a result, methods such as TO-hours, GTO-hours, and the Adaptive Temperature Threshold (ATG) are often used to assess the thermal performance of the existing housing stock. To evaluate their applicability, interview participants were asked to reflect on the effectiveness of current standards for new construction and whether these could be extended to existing buildings. Although this topic was not explicitly addressed in the resident questionnaire—due to the absence of legal obligations—some respondents referred in open comments to government rules they must follow, when they want to apply cooling strategies, which are discussed further in this chapter.

- **Interview**

The technical specialist from ISSO emphasized that the ATG approach can be difficult to interpret, as it is based on fluctuating outdoor temperatures and assumes a certain degree of behavioral adaptation by occupants. Although the physiologist argued that the comfort range can expand when adaptive control is embedded—and that simulation models using dynamic reference years may show acceptable indoor temperatures—these models often fail to reflect real-life behaviors, such as the inconsistent or incorrect use of natural ventilation (e.g., opening windows). This makes the predictive reliability of such tools questionable in practice. In addition, the TO and GTO method, which is based on the PMV/PPD model, was criticized for its sensitivity to input parameters. As the technical expert noted, small changes in variables such as airspeed, clothing insulation, or metabolic rate can significantly alter the output, making results highly dependent on expert assumptions which is also supported by the research of Alders et al. (2024). Depending on these assumptions, the perceived overheating risk can either be over or underestimated, thereby reducing the objectivity of the method.

The Building Physics Consultant emphasized that although TO-juli and related standards are not legally required for existing buildings, housing associations increasingly use them as a reference when evaluating retrofit measures. However, he criticized the limited practical applicability: calculations often suggest overly strict interventions, such as applying solar control glazing or installing shading on north-facing facades. Some recommended solutions—like dark-tinted solar control glass—may help meet TO-juli requirements but can simultaneously reduce indoor daylight quality, an aspect of comfort not considered within the TO-juli framework. Froukje, from the Hitte in de Woning report from de Vries et al. (2024) added that the TO-juli calculations are conducted for the entire building, while in reality, not every room within a dwelling has the same comfort requirements from the occupants' perspective, further investigated and explained in Section 4.3.

Beyond these technical critiques, concerns were raised about the limited scope of TO-juli. The physiologist argued that the standard does not fully capture thermal comfort, as it neglects key physiological factors such as air velocity and humidity, which significantly influence how heat is perceived and regulated by the human body. Finally, the Housing Corporation pointed out that even at relatively low TO-juli values—below the official threshold—residents already begin to report discomfort. This suggests that the TO-juli standard may not align well with actual user experiences. They advocated for broader use of PMV-based models, which incorporate all six thermal comfort variables and offer a more comprehensive reflection of perceived comfort. Notably, these models also acknowledge a tolerable dissatisfaction rate of 5–10%, allowing for a more realistic and occupant-centered approach to evaluating indoor thermal conditions.

- **Questionnaire**

Since residents are not currently required to implement measures against overheating in existing dwellings, the questionnaire did not directly address this topic. However, in the open-response section, several participants noted that certain cooling interventions—such as upgrading single to double glazing, installing external shading, or adding façade greenery—are not always permitted. In particular, these modifications may require formal approval or be prohibited entirely for heritage-listed buildings (rijksmonumenten). This underscores how regulatory constraints can directly limit residents' ability to implement cooling strategies.

Furthermore, multiple respondents pointed out that there is generally greater public knowledge about heating in winter than about cooling in summer. This perception is reflected in the questionnaire results, which show that heating strategies are more commonly implemented than cooling measures. As one participant noted:

"I believe people know more about heating than about cooling. That's why education on low-impact, low-cost, and low-tech cooling methods—simple tips and tricks, especially for young and elderly people—is really necessary, in my opinion."

4.3 Preference for the Timing and Location of Thermal Comfort

As described in Section 4.2, Froukje de Vries explained that the TO-juli standard measures overheating at the whole-building level, without distinguishing between individual rooms or considering the specific times when occupants require thermal comfort in those spaces. In contrast, the questionnaire responses explicitly highlight which rooms require the most cooling and when residents are typically at home. The interviews further clarify how design priorities are established, and when designers currently consider thermal comfort to be most critical—whether in summer or winter—along with their underlying reasoning.

- **Interview**

All interviewees confirmed that current building sustainability efforts are primarily focused on optimizing winter comfort, although it is expected that—due to increasing awareness of heat stress and climate change—the focus will gradually shift toward the prioritization of summer comfort.

The continued emphasis on winter comfort was specifically highlighted by the Housing Corporation, the Association of Housing Corporations, and both technical advisors. They explained that winter-oriented measures have a direct impact on reducing energy bills and lowering CO_2 emissions. In contrast, most Dutch dwellings currently lack active cooling systems, which means that the implementation of passive or low-energy cooling strategies does not yet contribute to those same energy or emission targets.

Furthermore, as noted by the Association of Housing Corporations, measures aimed at improving winter comfort do not always align with those needed for summer comfort. While better insulation can initially help keep heat out, once excess heat enters the building, it tends to linger longer if ventilation is insufficient. In some cases, sustainability measures may even exacerbate indoor overheating, underscoring the importance of integrating both winter and summer comfort considerations from the beginning of any renovation strategy.

- **Questionnaire**

Participants were asked to indicate which rooms they considered most important to keep cool during hot periods. Across all demographics—including housing type, gender, and age group—the bedroom was overwhelmingly prioritized (89%), followed by the living room (9%) (Figure 4.3, left). This aligns with the finding that 68% of respondents preferred thermal comfort during the night rather than during the day (Figure 4.3, middle).

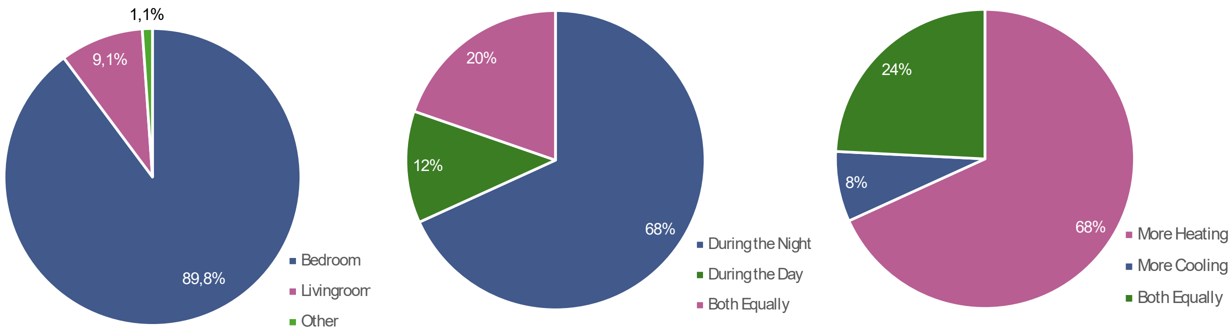


Figure 4.3 – Prefered Room (Left), Prefered Moment of the Day (middle), Prefered Cooling or Heating needs (right) for Maintaining Thermal Comfortable (Own work, 2025)

Furthermore, 90% of respondents reported being at home primarily between 20:00 and 08:00, with 59% also present between 16:00 and 20:00 (Figure 4.4). All respondents who prioritized the living room—or, in one case, a home office—for cooling were present during daytime hours. However, many of them still indicated that nighttime comfort was more important than daytime comfort, which suggests a less straightforward relationship between occupancy and perceived comfort needs. These patterns may be influenced by the sample's age distribution: with only 2% of respondents above retirement age, it is likely that most participants are away from home during the day due to work or education-related commitments.

This finding is supported by de Vries et al. (2024), who found that only 27% of participants preferred thermal comfort during the night, compared to 50% during the day and 23% in the evening. In that study, 56% of respondents were above retirement age, and 48% reported spending most of the day at home during hot periods.

Additionally, respondents were asked to specify their perceived lower and upper comfort thresholds, as introduced in Section 4.1, and whether they generally require more cooling or heating throughout the year to meet these thresholds. As shown in Figure 4.3 (right), nearly 68% of respondents indicated that they need to heat more frequently throughout the year, compared to only 24% who reported needing to cool more often.

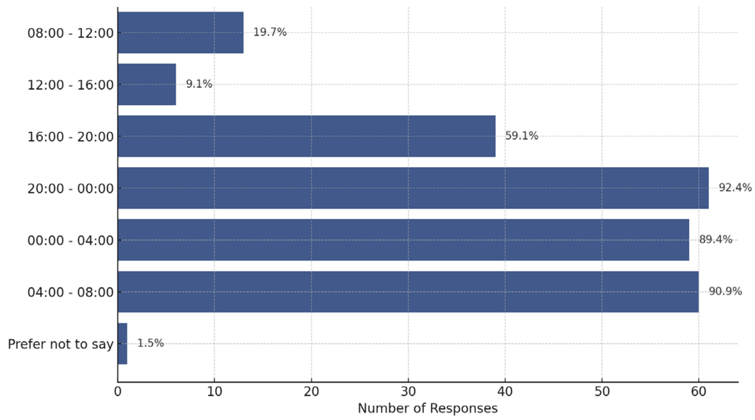


Figure 4.4 - Occupancy of Residents in their Homes (own work, 2025)

4.4 Type of Cooling Strategies

In all conducted interviews, participants were asked to identify the most practical strategies for mitigating overheating in residential buildings. In the questionnaire, respondents were also asked to indicate which cooling strategies they currently use, how frequently they apply them, how effective they perceive them to be, and which attributes they consider most important in a cooling solution.

Given that this thesis addresses the need for alternatives to the growing adoption of air conditioners in the Netherlands (Rovers, 2023), and that ceiling fans, while not yet widely used, appear to be an effective solution according to Raftery et al. (2023), both strategies are examined in more detail in the following sections.

- Interview

The Technical Installations Advisor emphasized that, aside from improvements to the building envelope—such as better insulation and optimized glazing—external shading is the only passive solution that can meaningfully reduce overheating, particularly for housing associations. This view was supported by the Building Physics Consultant, who added that in existing buildings, parameters like orientation, window-to-wall ratio, and overhangs are typically fixed and cannot easily be modified. Moreover, both experts noted that while improved insulation benefits both winter and summer conditions, it may actually increase overheating risks if not paired with sufficient night-time ventilation. Therefore, while insulation and double glazing remain essential, effective ventilation strategies are crucial.

From an operational perspective, however, housing associations approach shading measures differently. Both the Association of Housing Corporations and the Housing Corporation noted that external shading does not directly contribute to CO_2 reduction or lower energy bills. Given the pressure to meet national climate targets for 2050—particularly the reduction of natural gas consumption—housing corporations tend to prioritize investments in envelope upgrades and glazing improvements, which have a measurable impact on energy performance. Shading is generally only considered if it serves as a substitute for active cooling measures like air conditioning.

Additionally, both the Association of Housing Corporations and Housing Corporation pointed to the considerable maintenance and technical demands of external shading systems, particularly in multi-story buildings where high-access equipment is required. These logistical challenges make shading a relatively costly investment. Nevertheless, the technical specialist from ISSO highlighted that shading solutions do not need to be expensive or technologically complex. Simple, low-cost alternatives—such as installing awnings or fabric shades in gardens or on balconies—can also effectively block direct solar radiation and offer substantial thermal benefits.

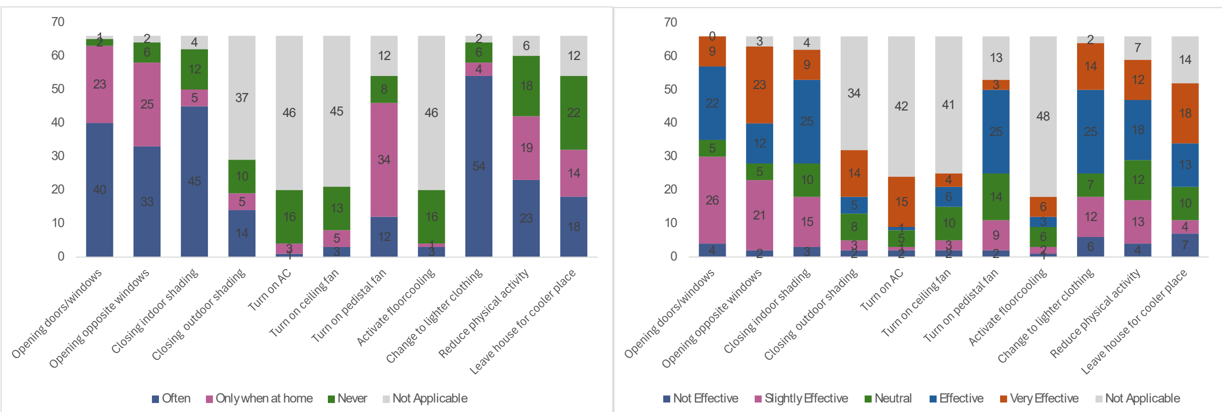


Figure 4.5 – Frequency of Use (Left) and Perceived Effectiveness (Right) of Cooling Strategies (Own work, 2025)

- ### Questionnaire

Figure 4.5 (left) illustrates the frequency with which each cooling strategy is used, based on responses from participating residents. Opening doors and windows, closing indoor shading, and wearing lighter clothing emerged as the most frequently applied strategies. In addition, opening doors and windows and using pedestal fans are often employed, though primarily only when residents are at home. In contrast, air conditioning, outdoor shading, ceiling fans, and floor cooling were marked as not applicable by more than half of respondents, and otherwise largely reported as never used.

Figure 4.5 (right) also presents respondents' perceptions of the effectiveness of the same strategies. Opening opposite windows was rated as "very effective" by the highest number of participants, followed by leaving the house for a cooler place. Changing to lighter clothing was most commonly evaluated as "effective" to "very effective" overall, followed by opening opposite windows and closing indoor shading.

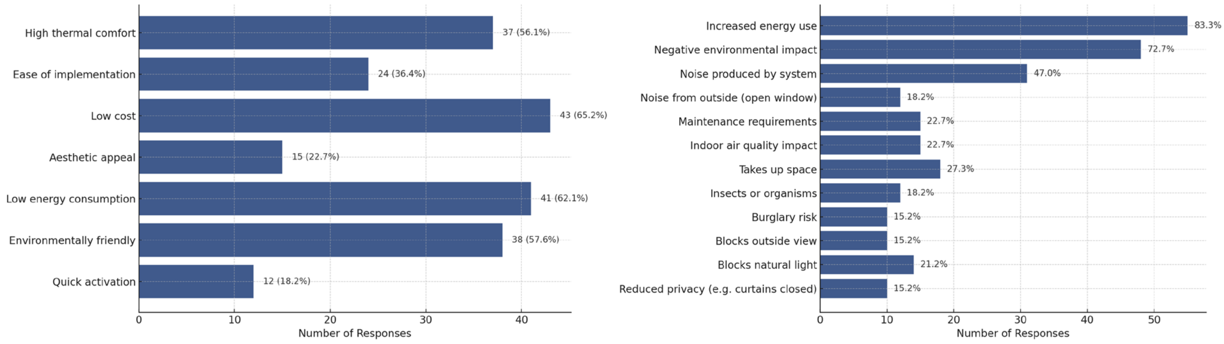


Figure 4.6 - Three aspect considered important for implementation (left) and negative side effects of cooling strategies (right) (own work, 2025)

Although the relationship between perceived effectiveness and actual usage is not directly observable, respondents were asked to identify their top three reasons for choosing a cooling strategy (Figure 4.6, left) as well as potential negative side effects that would discourage its adoption (Figure 4.6, right). The results indicate that residents strongly prioritize cooling strategies that are low-cost (67%), energy-efficient (62%), and environmentally friendly (58%)—even slightly more than the perceived improvement of thermal comfort (56%). These preferences align closely with the most frequently cited barriers to adoption: increased energy consumption (83%), negative environmental impact (73%), and device noise (47%). Taken together, these findings suggest that the ideal cooling solution for most respondents would be comfortable, affordable, sustainable, and quiet.

What stands out is that achieving high thermal comfort—while considered important by approximately half of the respondents—does not appear to be the sole driver of cooling strategy choices. This may explain why, as shown in Figures 4.5, the most frequently used cooling strategies are not necessarily perceived as the most effective. It is likely that practical considerations such as cost, energy consumption, created noise and environmental impact outweigh perceived effectiveness when it comes to actual implementation.

A factor that also influences the implementation of cooling strategies is the overall budget available to residents. As shown in Figure 4.7 (left), most respondents reported a summer cooling budget of €50–150 (39.4%), while 31.8% indicated they could allocate more than €600. Despite these figures, 57.6% stated they still prioritized winter comfort over summer comfort in terms of budget allocation (Figure 4.7, right). Given that 70% of respondents fall within a summer cooling budget range of €0–300, the afford ability and feasibility of implementing certain cooling technologies—particularly those with higher upfront costs—are inherently constrained. Notably, all respondents who reported a budget above €600 live in owner-occupied dwellings and are typically over the age of 55. This suggests that both housing tenure and age may influence not only disposable income but also the perceived value of long-term investments in summer comfort.

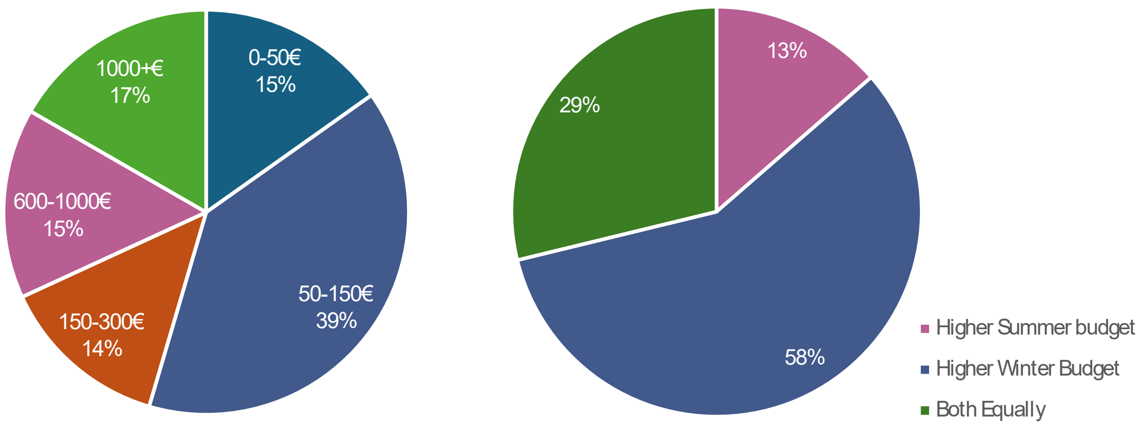


Figure 4.7 - Budget for Cooling (left) and Priority for Summer or Winter Budget (right) (own work, 2025)

4.4.1 Airconditioners

- Interview

Another alternative for cooling residential buildings is the implementation of air conditioning (AC) systems. While all interviewees agree that AC should be treated as a last resort, their perspectives on when and how to apply this technology differ. These views are reflected in the decision-making framework illustrated in Figure 4.8.

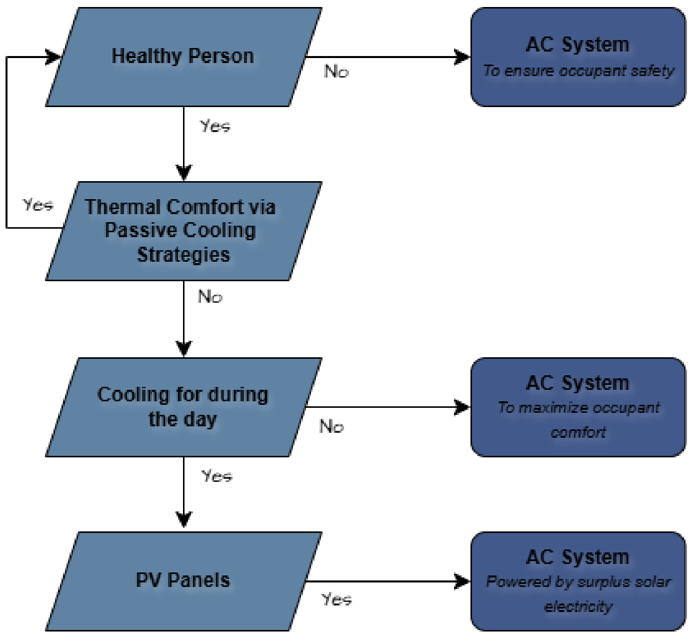


Figure 4.8 - Decision-making Framework for Implementing an Airconditioner (own work, 2025)

The first consideration involves the occupant's health condition. All experts concur that if a resident is vulnerable—such as elderly or in poor health—and unable to regulate body temperature or acclimate effectively, the use of AC becomes a necessity to ensure safety. If the occupant is healthy, the next step is to evaluate whether thermal comfort can be achieved via passive cooling strategies, such as improving envelope insulation, optimizing glazing, and installing external shading. If these measures are insufficient, financial and practical considerations come into play. The Association of Housing Corporations stresses that for most housing associations, cost is the main barrier: a large portion of rental income (approximately 70%) is already allocated to maintenance and sustainability efforts. Adding AC units would not only require a significant investment but also add recurring maintenance costs—estimated at around €100 per unit per year. In contrast, the ISSO technical expert suggests a more dynamic perspective, questioning whether current surpluses in solar electricity could justify increased use of ACs. However, the Housing Corporation notes that these surpluses occur during the day, while most residents are away. As such, direct use of surplus solar energy for cooling is limited unless cooling is also needed during daytime hours. Thus, if cooling is needed during the day, and the household is equipped with photovoltaic (PV) panels, using AC powered by surplus solar electricity becomes a more justified and efficient strategy.

If cooling is primarily required at night, particularly in bedrooms, the Architect acknowledges that an AC may be included in renovation designs—but only in high-end upgrades where occupants demand maximum comfort. However, this is countered by the physiologist, who warns that reliance on AC may reduce the body's ability to acclimate to higher temperatures over time. Still, the architect adds that rising electricity prices naturally deter overuse, maintaining a balance between comfort and energy-conscious behavior.

- Questionnaire

Of the 66 residents who responded to the questionnaire, only four reported owning and using an air conditioning unit. This is significantly lower than the findings reported by TNO, where nearly 30% of the 1,000 respondents indicated they used air conditioning (Rovers, 2023). In that sample, the main motivations for purchasing an air conditioner were the desire to sleep better (54%) and to increase thermal comfort in cooler rooms (50%). Additionally, 17% of respondents without an air conditioning unit indicated they were considering purchasing one in the coming years, according to the same TNO report.

According to the TNO report, the main reasons for not purchasing an air conditioner were concerns about energy consumption (51%) and purchase costs (55%). These were followed by 21% of the respondents who did not consider it necessary despite high indoor temperatures, 32% who believed it was harmful to the environment, and 23% who felt that air conditioners produce excessive noise (Keuchenius, 2023; Rovers, 2023). Similarly, respondents to the questionnaire in this study cited general negative side effects of cooling technologies as reasons for not adopting them (Figure 4.6, right). Specifically, 84% expressed concerns about increased energy consumption, 73% mentioned negative environmental impacts, and 47% were concerned about noise produced during use.

Although the question in this study did not specifically refer to air conditioners, these three concerns align closely with known drawbacks of air conditioning systems. When considered alongside the findings from the TNO report, it is reasonable to suggest that such perceived disadvantages may contribute to the reluctance to adopt air conditioning among this study's respondents. However, further targeted research would be needed to confirm this link explicitly with these respondents.

4.4.2 Ceiling Fans

- Interview

Although the interviewees demonstrated considerable knowledge of thermal comfort models, regulatory frameworks, and available cooling technologies, none initially mentioned the use of increased airspeed through fans as a viable cooling strategy. When specifically asked about their views, the ISSO technical specialist described fans as a highly accessible and low-threshold solution compared to other active cooling methods. While fans do not significantly lower air temperature, they can meaningfully enhance perceived thermal comfort through increased air movement. However, this effect is not accounted for in the TO-juli method, which may contribute to the limited adoption of fans as a cooling strategy in the Netherlands.

The Technical Installations Advisor noted that ceiling fans are rarely integrated into Dutch building design practices, in contrast to regions such as Asia and the United States, where their use is far more widespread. However, the Architect indicated that fans are in fact regularly considered during the design phase. In addition to designing windows that can be opened on opposing facades to facilitate natural cross-ventilation, fans are viewed as effective tools to enhance indoor air movement. In buildings with tall interior spaces, fans can also be used in winter to redistribute warm air from the ceiling back downwards, helping to distribute warm air more evenly throughout the room. The Building Physics Consultant acknowledged the potential advantages of fan use but expressed skepticism about their effectiveness in bedrooms—particularly when individuals are lying under blankets and may not directly feel the airflow.

From the perspective of both the Association of Housing Corporations and Housing Corporation, allowing residents to use their own ceiling fans is considered a suitable and effective approach to improving personal comfort. Ceiling fans offer an occupant-controlled solution that does not require prior approval, unlike fixed installations such as exterior shading systems or air conditioning units, which are subject to regulatory restrictions and approval procedures.

- **Questionnaire**

Ceiling fans were reported as not applicable by 68% of questionnaire respondents and were therefore generally not used or evaluated for effectiveness. This contrasts with findings by Raftery et al. (2023), which indicate that over 80% of U.S. households have at least one ceiling fan. In contrast, pedestal fans are used by 70% of respondents in this study, and more than half of the participants in the study by De Vries et al. also reported using a fan for cooling. In this study, only 3% of respondents rated pedestal fans as ineffective. Given that both fan types enhance thermal comfort by increasing air velocity—differing mainly in size, placement, and mobility—it may be assumed that ceiling fans could be perceived as equally effective if implemented. However, due to their larger size, ceiling fans may consume more energy, require additional materials, and produce more noise—factors identified by respondents as key disadvantages of cooling technologies, as illustrated in Figure 4.6 (right).

4.5 Occupants Behavior towards Cooling Stragies

Occupant behavior in residential buildings plays a key role in selecting appropriate thermal comfort models. When applying the PMV model, the influencing factors—such as clothing insulation, metabolic rate, ventilation levels, and indoor temperature distribution—are directly affected by how occupants behave inside their homes. For the adaptive comfort model, occupant behavior is equally relevant, as it assumes that people can adjust to varying thermal conditions. This raises the question of whether the assumed adaptive range of comfort is both realistic and applicable in practice, depending on actual opportunities for behavioral adaptation.

- **Interview**

All interviewees agreed that occupant behavior plays a critical role in the effective use of cooling strategies and the resulting thermal comfort. A technical specialist from ISSO highlighted that, within their own homes, residents are not bound by clothing norms and can also engage in less physically demanding activities during hot periods. Moreover, both the ISSO specialist and the physiologist emphasized that many residents lack sufficient knowledge about how to effectively cool their homes and themselves. They stressed the need for targeted information and education to support behavioral improvements. At present, Housing Corporation addresses this issue reactively: when residents report overheating complaints, a staff member visits the home to provide a flyer with practical tips on how to cool the space effectively.

The physiologist further explained that sudden exposure to extreme temperature fluctuations makes it challenging for the human body to acclimatize. To build resilience during extreme heat events, individuals should begin adapting to elevated temperatures early in the season by gradually conditioning their bodies—thus reducing reliance on mechanical cooling systems also stated in de study of Alders et al. (2025). Following the deadly heatwaves in the Netherlands in 2003 and 2019, which resulted in significant excess mortality, subsequent declines in heat-related deaths during later heatwaves may partly be attributed to increased public awareness and improved acclimatization practices. This was recently confirmed by a study from the Dutch National Institute for Public Health and the Environment (RIVM, 2025), which found that recent heatwaves have heightened public awareness. The study also credits the implementation of the Dutch National Heat Plan and its associated media coverage with contributing to reduced excess mortality during the summer months in the Netherlands.

The Housing Corporation noted that tenant turnover in residential units leads to new occupants with differing comfort expectations and behavioral habits. This variability complicates the consistent application of behavior-dependent solutions. For example, the corporation expressed skepticism about relying on manual solar shading, as it needs to be lowered during the day when residents are often not at home. Although central control of shading systems could provide a solution, this approach may conflict with occupants' sense of autonomy, potentially leading to dissatisfaction. While these observations are largely based on experience rather than empirical evidence, it is clear that resident behavior and perception influence the decision-making process around implementing such technologies.

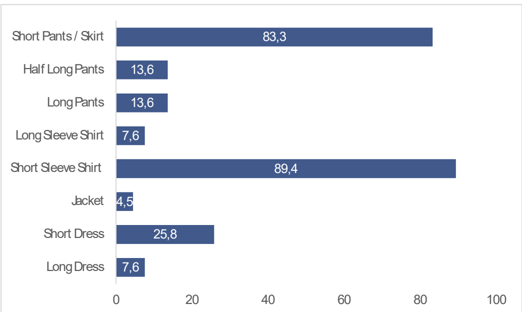
The Building Physics Consultant emphasized that good building design—minimizing dependence on occupant behavior—is essential for maintaining thermal comfort. While a sense of personal control can positively influence how users perceive their indoor environment, even well-informed occupants often forget to ventilate or adjust systems appropriately, resulting in overheating. The Technical Installations Advisor confirmed that the primary focus of consultants is to comply with client specifications and regulatory requirements. Nevertheless, occupant behavior is considered in design decisions: for instance, in mechanically ventilated buildings, operable windows are deliberately restricted to prevent conflict with the system's operation. Thermostats are also installed to give occupants a perceived sense of control, as this has been shown to improve thermal satisfaction.

- **Questionnaire**

As highlighted in the questionnaire and previous subsections, various behavioural aspects of occupants significantly influence both the selection and implementation of cooling strategies. Residents tend to apply strategies that are feasible within the physical and practical constraints of their homes. However, these choices do not always align with the strategies perceived as most effective, suggesting that factors such as cost, energy use, or availability often outweigh perceived thermal benefits in driving decision-making.

Occupancy patterns also play a critical role. Strategies such as opening windows or using fans are typically employed only when residents are at home—most often during the evening and nighttime rather than during daytime hours (Figure 4.5, left). The study by de Vries et al. identified key barriers that prevent nighttime window use even when occupants are home: noise (23%), fear of burglary (28%), and insects (18%). Furthermore, the assumption made by some housing associations that external shading will be lowered during the daytime to reduce solar gains does not fully align with observed occupant behaviour, as many residents are not home to perform such actions. Similarly, the expectation that air conditioning systems could be powered by surplus solar energy during the day may be overly optimistic, given that most cooling demand occurs during the evening and night, particularly in bedrooms.

In addition, two behavioural aspects were evaluated that directly relate to input parameters of the PMV model. First, respondents reported typical summer clothing—mainly shorts and short-sleeved shirts—which corresponds to lower clothing insulation values than those commonly assumed in studies such as Huizenga et al. (2024) and Alders et al. (2024) (Figure 4.9, left). Second, respondents identified a consistent set of daily summer activities—such as sleeping, reading, watching television, working, and cooking—supporting the application of similar metabolic rate assumptions as those used in prior residential comfort research (Figure 4.9, right).



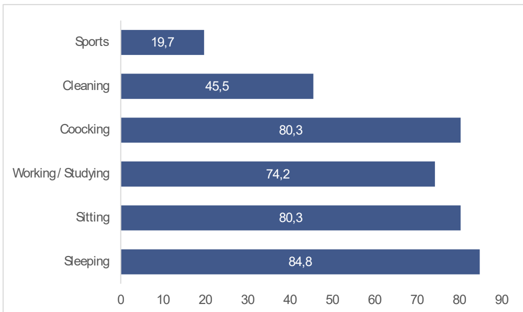


Figure 4.9 - Summer Clothing (left) and Activity of Respondents (own work, 2025)

4.6 Responsible for Implementation

The question of who holds responsibility for implementing cooling strategies in Dutch dwellings is particularly relevant, as those who benefit most—the residents—do not always have the means or authority to apply such measures themselves. Conversely, those with the ability to implement these strategies—such as housing providers—may lack the financial resources or the influence to ensure that residents use them effectively. This tension highlights a structural disconnect, which is further explored through the findings from both the interviews and the questionnaire.

- **Interview**

Both the ISSO technical specialist and the Technical Installations Advisor emphasized that housing associations are well-positioned to implement long-term cooling strategies. However, the split incentive—where tenants pay the energy bills while associations carry the investment costs—creates a major barrier. Without direct financial benefit, housing associations have little incentive to pursue sustainable cooling upgrades unless mandated by law. The Housing Corporation confirmed this issue, noting that if they were responsible for energy costs—such as through an inclusive rent model—they would have a greater interest in reducing energy demand. Yet, current regulations only allow them to charge tenants for actual energy use, making it impossible to recoup the cost of high-efficiency systems like heat pumps or WKO. As non-profits, such investments are financially unfeasible. Moreover, since cooling is rarely metered separately, there are no immediate cost savings for tenants unless these systems replace air conditioning.

At the same time, internalizing energy costs entirely could remove incentives for residents to conserve energy. This concern is already visible in new-build projects, where cost-benefit balancing is complex. The Architect agreed, noting that the electricity bill is often the only real deterrent against overusing air conditioning. Without this, users may become overly reliant on mechanical cooling—contrary to the physiologist's view that gradual acclimatization improves resilience.

The architect emphasized that the ultimate responsibility for implementing cooling strategies lies most clearly with the government. In his view, all other stakeholders involved in the building process—such as consumers, installers, developers, architects, and contractors—are primarily driven by economic interests or dependent on client decisions. As they explained:

> *"The consumer logically chooses the cheapest option, the installer selects what is technically reliable and comes with warranty, and the developer prioritizes profitability. Although architects often propose sustainable and comfort-enhancing solutions, these are frequently overshadowed by financial considerations. That is why only the government can truly make an impact—through regulation and standardization, it can establish binding requirements for summer comfort, creating a level playing field that compels all actors to comply."*

As the Technical Installations Advisor explained, many sustainable interventions require considerable up-front investment and may not yield short-term returns. Therefore, unless mandated through regulation, such investments typically depend on voluntary ambition, which varies widely among associations.

- **Questionnaire**

Although the questionnaire did not explicitly ask respondents whom they consider responsible for implementing cooling measures in their homes, ownership status was recorded and provides valuable context. As shown in Figure 4.10, 11% of respondents live in social housing. In such dwellings, tenants may install temporary measures that can be removed upon vacating the property. However, for more permanent or external interventions—such as outdoor shading, air conditioning units, or façade greening—tenants typically require prior approval from the housing corporation, or these measures must be initiated by the corporation itself.

Among homeowners, who represent 39% of the respondents, residents generally have greater autonomy in modifying their homes. Nonetheless, they are still subject to regulatory constraints, such as the need for permits. Additionally, several respondents mentioned that homeowners' associations (VvEs) may impose approval processes, which can also limit the feasibility of certain cooling interventions.

Finally, in the case of private rental properties, similar restrictions often apply. Tenants typically require the landlord's approval for permanent or visible alterations. Only temporary cooling solutions—such as portable fans or mobile air conditioning units—that can be removed without leaving permanent traces are generally permitted without prior consent.

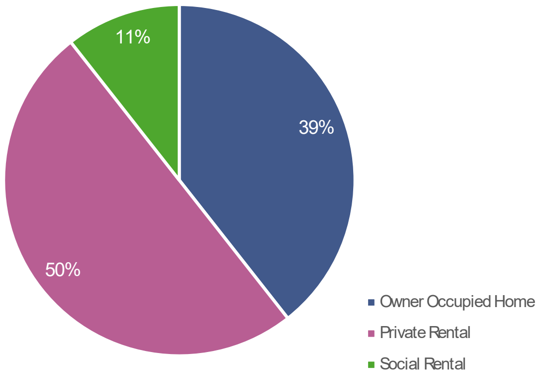


Figure 4.10 - Residential Types (own work, 2025)

4.7 Discussion

4.7.1 Summary of Key Findings

This chapter presents insights from interviews with 11 stakeholders and a questionnaire completed by 66 Dutch residents. Together, these findings address the sub-question: '*What are the perspectives of stakeholders from various sectors of the built environment regarding the implementation and perceived effectiveness of cooling strategies for existing residential buildings?*' presented below:

Interview Findings

- Thermal comfort experts confirmed that the six variables used in the PMV model remain the most accurate approach for assessing thermal comfort.
- Design professionals often apply simplified thresholds, typically aiming for a maximum summer indoor temperature of 25°C.
- There are currently no mandatory regulations addressing overheating in existing residential buildings.
- Guidelines such as the Adaptive Temperature Threshold (ATG) assume behavioural adaptations (e.g., opening windows), which broaden the acceptable comfort range. However, these adaptations are not consistently applied in practice, leading to potential overestimation of comfort levels.
- Static TO/GTO-hour simulations rely on assumptions (e.g., equal air and radiant temperature, fixed airspeed, humidity, clothing insulation, and metabolic rate), which may result in inaccurate assessments. Dynamic simulations eliminate these assumptions, producing more precise outcomes.
- Thermal comfort standards (TO, GTO, ATG, TO-juli) do not account for room-specific occupancy patterns, potentially misrepresenting overheating in unoccupied spaces.
- Sustainability efforts in the housing sector predominantly focus on winter comfort in stead of summer comfort, as it has a direct impact on CO_2 reduction, energy use, and heating costs.
- High upfront investment, maintenance concerns, and the split incentive between owners and users deter the implementation of cooling solutions.
- In the absence of legal obligations, responsibility for mitigating overheating is often left to residents, who may lack the authority or means to take action.

Questionnaire Findings

- The preferred maximum indoor temperature among residents is relatively moderate, with 39% favouring a range of 21–23°C and 32% preferring 24–26°C.
- Tenants often require permission from landlords or housing corporations to implement cooling measures, creating further barriers.
- In owner-occupied homes, external interventions such as solar shading may still require approval from homeowner associations (VvEs).
- Despite reporting significant summer discomfort, residents allocate more financial resources to heating than to cooling.
- Residents value thermal comfort, low cost, environmental friendliness, and low energy use as the most important qualities of a cooling strategy.
- The most cited barriers to implementing cooling strategies are increased energy consumption, negative environmental impact, and noise, outweighing concerns such as aesthetics or ease of use.
- Reported summer clothing insulation levels were considerably lower than assumed in thermal models, with typical outfits yielding 0.25–0.3 clo values.
- Window ventilation was mostly used when residents were home, undermining assumptions of continuous natural ventilation.

4.7.2 Validation and Consistency with Previous Research

The validity of conducting interviews and surveys is inherently more complex to assess than that of simulation-based methods, as respondents can interpret and answer questions in multiple ways. In the interviews, stakeholders shared insights based on their professional expertise and practical experience. These perspectives do not necessarily represent the views of all actors within their sector, nor are they universally applicable to all residents. To strengthen validity, findings were systematically compared to existing literature. Where inconsistencies arose, results were only included in the conclusions if they were confirmed by multiple stakeholders or supported by questionnaire responses from several residents.

The questionnaire was open to all Dutch residents, regardless of prior knowledge of this study. Most questions focused on factual aspects—such as housing type, perceived thermal comfort, and past cooling behavior—ensuring a low barrier to participation and minimizing bias. Only the questions asking participants to rank different cooling strategies by perceived effectiveness or to indicate which factors influence their choice of cooling solutions may have been affected by prior knowledge or could change by repeated exposure to the survey. To minimise this effect, each person was asked to complete the questionnaire only once and was not given any prior information about the research topic.

While the sample may still have limitations, it expands upon the scope of de Vries et al. (2024), whose survey focused primarily on older residents in social housing. Notably, this study confirms several of the patterns identified by de Vries et al., thereby reinforcing the robustness and consistency of shared findings across different respondent groups.

4.7.3 Interpretation of Results

While the perspectives of stakeholders and residents may appear individually coherent, the results reveal inconsistencies across actors, rooted in a lack of shared knowledge and alignment. Justifications offered by one stakeholder were often contradicted by others, underscoring the diverse responsibilities, priorities, and practical constraints across the value chain.

Each actor appears to operate from their own internal logic or "truth," shaped by their specific position in the built environment value chain. This divergence highlights that there is no single explanation or solution for the lack of cooling interventions; rather, the problem is systemic and multifaceted. These findings emphasize the need for greater cross-sector communication and alignment, particularly when it comes to implementing passive and low-energy cooling strategies in existing residential buildings.

The study revealed that efforts to improve indoor thermal comfort continue to prioritise winter conditions. Contrary to the assumption that colder winters are seen as more problematic, interviews suggested that summer overheating is overlooked because interventions often lack measurable benefits, such as energy savings or CO_2 reductions. Without these incentives, building managers deprioritise such measures—even if they improve resident thermal comfort.

As a result, thermal comfort alone does not motivate action. Both interviewees and survey respondents agreed that an ideal strategy must be affordable, energy-efficient, environmentally sustainable, low-maintenance, and easily implemented without requiring external approval. External shading and green roofs are effective but often require institutional coordination. In contrast, interventions such as improved glazing, ceiling fans, and ventilation adjustments are more accessible and may also support winter comfort—thus overcoming split-incentive dilemmas.

4.7.4 Practical Implications

The lack of overheating regulation for the existing housing stock represents a significant barrier to implementation. While summer comfort is gradually becoming embedded in new construction standards—such as the Dutch TO-juli threshold—no such regulatory requirement exists for existing dwellings. This regulatory gap allows decision-makers to overlook summer thermal comfort, even when technically feasible solutions are available.

One potential policy lever could be the incorporation of overheating performance into energy labelling schemes. For example, homes that maintain less than 450 GTO-hours or 300 TO-hours during the summer period could qualify for an upgraded energy label, thereby encouraging homeowners to adopt passive and low-energy cooling strategies. Municipalities and housing associations could also be required to assess overheating risks as part of new tenancy agreements or major renovation efforts.

However, translating this into practice presents challenges. Current energy labels primarily reward permanent thermal improvements such as insulation and high-performance glazing—interventions that are difficult to reverse once installed. In contrast, solar shading and ceiling fans are relatively easy to remove after installation, potentially undermining their long-term impact on energy ratings. Green roofs, on the other hand, represent more permanent interventions and may be better suited for inclusion in performance-based certification schemes.

In parallel, there is an urgent need to promote cooling strategies that meet the diverse set of priorities expressed by both residents and building professionals. Without solutions that are not only technically effective, but also cost-efficient, environmentally sustainable, easy to maintain, and unobtrusive, the adoption of passive cooling measures will likely remain limited—allowing the growing reliance on energy-intensive air conditioning to persist.

4.7.5 Limitations

This study faced several limitations. First, ethics approval for the interviews and questionnaire required formal approval from the TU Delft data stewards, resulting in delays. As a consequence, data collection commenced only one month before the submission deadline. While ten interviews covered a broad range of perspectives, a larger sample with at least two representatives per sector would have allowed for more robust cross-validation.

Similarly, the 66 survey responses, though diverse, were primarily collected through first- and second-degree contacts. A larger, randomly sampled population—or a geographically targeted approach—would have improved generalisability. The timing of the survey in spring may also have influenced results, as participants might not recall previous summer discomfort accurately, or only remember the extreme weather events.

Finally, the study's limited timeframe restricted the ability to repeat the survey during different seasons. This could have mitigated temporal bias and improved the robustness of responses regarding seasonal thermal comfort.

4.7.6 Recommendations for Future Research

The next chapter evaluates passive and low-energy cooling strategies in terms of their effectiveness in improving thermal comfort. However, thermal performance alone is insufficient for practical implementation.

Future research should incorporate additional assessment criteria such as cost, energy use, environmental impact, ease of implementation, required approvals, and maintenance needs. These criteria would allow for a comprehensive multi-criteria decision framework, helping stakeholders determine whether a strategy could viably replace air conditioning—which continues to gain popularity despite its drawbacks.

The questionnaire results of this study are consistent with findings by Rovers (2023) and de Vries et al. (2024), which reinforces their credibility. However, a notable contradiction emerged: despite the increasing adoption of air conditioning, respondents cited high energy consumption, environmental impact, and noise as significant disadvantages. This suggests that the decision to install air conditioning may be more complex than commonly assumed. Future research should therefore explore the underlying motivations behind such decisions. Key questions include: under what conditions would residents consider installing air conditioning; what are their thresholds for thermal discomfort (e.g., maximum consecutive hours or days of overheating); which areas of the home are perceived as most problematic; and who they believe is responsible for implementing effective cooling measures.

Lastly, while this knowledge is increasingly well-documented in the academic literature, a critical next step lies in effectively transferring this knowledge to both designers and residents—ensuring that it is not only available but also understood and applied in practice.

5. Results of Building Simulations

5. Results of Building Simulations

Building on the insights gathered from the literature review, interviews, and questionnaire, this chapter presents dynamic building simulations to evaluate the effectiveness of various passive and low-energy cooling strategies in typical Dutch residential dwellings. Three common housing types—detached, terraced, and apartment buildings—are simulated, each incorporating two occupant window-opening behaviors (night ventilation and temperature-based ventilation), two ventilation types (single-sided and cross ventilation), and both existing and renovated construction profiles. Additionally, technical strategies such as solar shading, green roofs, and ceiling fans are assessed in combination with these behavioral and building-specific measures. Unlike previous studies that rely on static assumptions (e.g., air temperature equals radiant temperature, air velocity = 0.1 m/s, and humidity = 50%), these simulations dynamically calculate environmental parameters on an hourly basis. Table 5.1 summarizes the abbreviations used for each simulation scenario.

Results are presented as the number of summer hours during which the Predicted Mean Vote (PMV) exceeds 0.5—referred to as TO-hours under Dutch regulations—as well as the number of hours exceeding a PMV of 1, which indicates more severe thermal discomfort and potential health risks. These outcomes are benchmarked against Dutch regulatory thresholds for existing buildings: 300 TO-hours for PMV >0.5 and 100 hours for PMV >1 and are shown in graphs in Appendices 5.1-5.3.

These analyses address the research sub-question: *What combinations of passive and low-energy cooling strategies are most effective in reducing thermal discomfort across different Dutch housing typologies under future summer climate scenarios?* A strategy is considered more effective than another if it results in fewer total TO-hours, for both PMV >0.5 and PMV >1. This allows for a systematic comparison of behavioral and technical adaptations. However, it is also possible for a less effective strategy to remain below both regulatory thresholds and therefore still be considered sufficiently effective under Dutch standards.

		Single-Sided Ventilation		Cross Ventilation	
		Current Construction Rvalue = 0.15 - 2,50	Renovated Construction Rvalue = 1.70 - 3,50	Current Construction Rvalue = 0.15 - 2,50	Renovated Construction Rvalue = 1.70 - 3,50
Windows open at night	Bedroom	NV_SSV_CC_BR	NV_SSV_RC_BR	NV_CV_CC_BR	NV_CV_RC_BR
	Livingroom	NV_SSV_CC_LR	NV_SSV_RC_LR	NV_CV_CC_LR	NV_CV_RC_LR
Windows open when: 15°C < $T_{outside}$ < 27°C	Bedroom	TV_SSV_CC_BR	TV_SSV_RC_BR	TV_CV_CC_BR	TV_CV_RC_BR
	Livingroom	TV_SSV_CC_LR	TV_SSV_RC_LR	TV_CV_CC_LR	TV_CV_RC_LR

Table 5.1 - Abbreviations per Cooling Strategy (Own work, 2025)

Behavioral Window Opening Types
- Night Ventilation (NV): Windows are open from 21:00 to 07:00 and remain closed during the rest of the day.
- Temperature-Based Ventilation (TV): Windows are kept open as long as the outdoor temperature is between 15°C and 27°C.

Ventilation Types
- Single-Sided Ventilation (SSV): The room is modeled with one operable window facing the exterior, while the interior door remains closed.
- Cross Ventilation (CV): The room is modeled with operable windows on opposite façades of the dwelling, with interior doors modeled as open to allow airflow and thermal equalization between rooms.

Construction Types
- Current Construction (CC): Represents the existing thermal characteristics of the dwelling, including current R-values and glazing performance.
- Renovated Construction (RC): Reflects improved insulation and glazing, resulting in higher R-values in line with typical renovation practices.

5.1 Amount of TO Hours for a Detached Residence

5.1.1 Baseline Performance

Out of the 32 baseline scenarios, 8 comply with the Dutch TO thresholds—defined as a maximum of 300 summer hours where PMV > 0.5 and 100 hours where PMV > 1 (Table 5.2, top). A clear difference is observed between the two window-opening behaviours and the two ventilation types. In all cases, temperature-based ventilation—whether in the living room or the bedroom—leads to fewer TO-hours than night ventilation. Likewise, cross ventilation consistently results in lower TO-hours compared to single-sided ventilation.

A notable finding within the bedroom scenarios is that the combination of renovated construction and cross ventilation results in fewer TO-hours than the same ventilation strategy in the current construction. This improvement is not observed in single-sided ventilation scenarios or in any of the renovated living room cases. Additionally, the inclusion of ceiling fans in the baseline scenarios consistently reduces TO-hours and yields the highest number of compliant outcomes.

Another observation is that the bedroom consistently shows a higher number of TO-hours than the living room across all simulations. In the simulation setup, the living room is located on the ground floor and oriented south, whereas the bedroom is situated one floor above and faces north, receiving less direct solar radiation. In addition, the assumed activity levels and clothing insulation differ between the two spaces: the bedroom uses a clothing insulation value of 1.5 CLO and a metabolic rate of 0.7 met (representing sleeping conditions), while the living room uses 0.3 CLO and 1.1 met (representing typical daytime activities such as sitting and reading).

The most effective scenario for the living room involves temperature-based ventilation with current (non-renovated) construction, cross ventilation, and ceiling fans. For the bedroom, the most effective setup combines temperature-based ventilation with renovated construction, cross ventilation, and ceiling fans. Both scenarios also remain compliant without ceiling fans, although with slightly higher TO-hours.

5.1.2 Exterior Solar Shading

In Table 5.2 (middle), all baseline scenarios are recalculated with exterior solar shading applied to all solar-facing windows. The results show a reduction in TO-hours across all cases compared to the baseline, indicating that solar shading effectively reduces thermal discomfort. However, night ventilation scenarios still result in higher TO-hours than temperature-based ventilation and do not lead to compliance with the Dutch thresholds. Similar to previous results, the combination of renovated construction with cross ventilation proves more effective than either current construction with cross ventilation or renovated construction with single-sided ventilation.

For the living room, the most effective scenario combines solar shading and a ceiling fan with the same conditions as the baseline. The single-sided ventilation variant, however, follows closely. For the bedroom, the same holds true: combining solar shading and a ceiling fan with the baseline setup yields the best performance. Furthermore, the graphs in Appendix 5.1 show that not only does the total number of TO-hours decrease, but the proportion of hours exceeding PMV >1 declines more significantly than those exceeding PMV >0.5. This suggests that solar shading is also effective in reducing the severity of overheating.

5.1.3 Green Roof

The implementation of a green roof reduces TO-hours across all scenarios compared to the baseline (Table 5.2, bottom), with a more noticeable effect in current constructions. In renovated cases, the added benefit is smaller. Although technically effective, the reductions are minimal and likely imperceptible. Still, the overall ranking of strategy effectiveness remains unchanged. Where the combination of a green roof and ceiling fan yields the lowest TO-hours for both the living room and the bedroom.

Detached

Ventilation	Room	Baseline: Single-Sided Ventilation, Current Construction Rvalue = 0.15 - 2,50	Baseline: Single-Sided Ventilation, Renovated Construction Rvalue = 1.70 - 3,50	Baseline: Cross Ventilation, Current Construction Rvalue = 0.15 - 2,50	Baseline: Cross Ventilation, Renovated Construction Rvalue = 1.70 - 3,50	Baseline & Ceiling Fans: Single-Sided Ventilation, Current Construction Rvalue = 0.15 - 2,50	Baseline & Ceiling Fans: Single-Sided Ventilation, Renovated Construction Rvalue = 1.70 - 3,50	Baseline & Ceiling Fans: Cross Ventilation, Current Construction Rvalue = 0.15 - 2,50	Baseline & Ceiling Fans: Cross Ventilation, Renovated Construction Rvalue = 1.70 - 3,50
Night Ventilation from 21:00 - 07:00	Bedroom	1113	1329	577	513	931	1271	443	368
	Livingroom	1122	1298	827	1215	916	1289	529	1133
Temperature based Ventilation $15°C < T_{outside} < 27°C$	Bedroom	346	437	**171**	**134**	**194**	313	**96**	**77**
	Livingroom	214	469	**141**	307	**91**	167	**69**	120

Detached

Ventilation	Room	Shadings: Single-Sided Ventilation, Current Construction Rvalue = 0.15 - 2,50	Shadings: Single-Sided Ventilation, Renovated Construction Rvalue = 1.70 - 3,50	Shadings: Cross Ventilation, Current Construction Rvalue = 0.15 - 2,50	Shadings: Cross Ventilation, Renovated Construction Rvalue = 1.70 - 3,50	Shadings & Ceiling Fans: Single-Sided Ventilation, Current Construction Rvalue = 0.15 - 2,50	Shadings & Ceiling Fans: Single-Sided Ventilation, Renovated Construction Rvalue = 1.70 - 3,50	Shadings & Ceiling Fans: Cross Ventilation, Current Construction Rvalue = 0.15 - 2,50	Shadings & Ceiling Fans: Cross Ventilation, Renovated Construction Rvalue = 1.70 - 3,50
Night Ventilation from 21:00 - 07:00	Bedroom	872	1232	340	238	624	1088	228	139
	Livingroom	535	1195	370	954	413	910	240	608
Temperature based Ventilation $15°C < T_{outside} < 27°C$	Bedroom	283	379	**132**	**80**	**153**	281	**74**	**51**
	Livingroom	**51**	193	**47**	**146**	**24**	**92**	**17**	**82**

Detached

Ventilation	Room	Green roof: Single-Sided Ventilation, Current Construction Rvalue = 0.15 - 2,50	Green roof: Single-Sided Ventilation, Renovated Construction Rvalue = 1.70 - 3,50	Green roof: Cross Ventilation, Current Construction Rvalue = 0.15 - 2,50	Green roof: Cross Ventilation, Renovated Construction Rvalue = 1.70 - 3,50	Green roof & Ceiling Fans: Single-Sided Ventilation, Current Construction Rvalue = 0.15 - 2,50	Green roof & Ceiling Fans: Single-Sided Ventilation, Renovated Construction Rvalue = 1.70 - 3,50	Green roof & Ceiling Fans: Cross Ventilation, Current Construction Rvalue = 0.15 - 2,50	Green roof & Ceiling Fans: Cross Ventilation, Renovated Construction Rvalue = 1.70 - 3,50
Night Ventilation from 21:00 - 07:00	Bedroom	1074	1328	485	449	876	1269	344	297
	Livingroom	1084	1298	753	1213	855	1289	430	1122
Temperature based Ventilation $15°C < T_{outside} < 27°C$	Bedroom	325	424	**146**	**120**	**188**	309	**84**	**73**
	Livingroom	191	456	**114**	285	**85**	160	**54**	**116**

Table 5.2 - TO Exceedance per Situation for the Detached Residence (Own work, 2025)

The tables present the number of TO hours—defined as the total summer hours during which PMV > 0.5 is exceeded—for each combination of cooling strategies. To ensure consistency across all tables in this thesis, the maximum value for the red color scale is set at 1550 TO hours. This allows for a uniform visual comparison of performance. Values shown in bold blue indicate compliance with Dutch guidelines, meaning that PMV > 0.5 is exceeded for no more than 300 hours, and PMV > 1 is exceeded for no more than 100 hours.

1550 TO Hours

0

X = complience

5.2 Amount of TO Hours for a Terraced Residence

5.2.1 Baseline Performance

Out of the 32 baseline scenarios, only 4 comply with the Dutch TO thresholds—defined as a maximum of 300 hours with PMV > 0.5 and 100 hours with PMV > 1 (Table 5.3, top). All compliant scenarios apply to the living room and feature temperature-based ventilation combined with ceiling fans.

Temperature-based ventilation consistently results in fewer TO-hours than night ventilation, and cross ventilation outperforms single-sided ventilation in all cases. In general, the current construction scenario yields better thermal performance than the renovated variant. An exception is observed in the bedroom scenarios, where the combination of renovated construction and cross ventilation produces fewer TO-hours than the same strategy applied to the current construction. Additionally, the bedroom consistently exhibits a higher number of TO-hours compared to the corresponding living room scenarios. Both spaces are south-facing, with the living room located on the ground floor and the bedroom one level above. The simulation assumptions differ between the two: the bedroom includes a higher clothing insulation value (1.5 CLO), representing bedding and sleepwear, compared to 0.3 CLO (light summer clothing) in the living room. The metabolic rate is lower in the bedroom (0.7 met for sleeping) than in the living room (1.1 met for seated activities).

The most effective baseline setup for the living room is temperature-based ventilation with current construction and ceiling fans. This applies to both single-sided and cross ventilation, yielding similar results (87 and 81 TO-hours, respectively). For the bedroom, the most effective configurations are temperature-based ventilation with cross ventilation and either current or renovated construction, with nearly identical TO-hour values (306 and 311, respectively) when ceiling fans are used.

5.2.2 Exterior Solar Shading

The first immediate observation is that the terraced residential buildings with solar shading demonstrate lower TO-hours compared to the same scenarios in the baseline configuration (Table 5.3, middle), resulting in compliance in eight scenarios. In particular, the living room with temperature-based ventilation and solar shading—both with and without ceiling fans—achieves compliance with the Dutch thresholds.

Moreover, the graphs in Appendix 5.2 show a substantial reduction in total TO-hours across all scenarios. Importantly, the number of hours exceeding PMV > 1 decreases more significantly than those exceeding PMV > 0.5, suggesting that the severity of thermal discomfort is reduced. As in the baseline, temperature-based ventilation proves more effective than night ventilation, and cross ventilation remains more effective than single-sided ventilation. With the exception of the renovated bedroom scenarios, current construction again results in lower TO-hours than renovated construction.

For both the living room and bedroom, the most effective configurations mirror the baseline setup but with the addition of solar shading. In the living room, combining shading with ceiling fans produces the lowest number of TO-hours overall.

5.2.3 Green Roof

The implementation of a green roof generally leads to a slight reduction in total TO-hours compared to the baseline, as shown in Table 5.3 (bottom). However, the number of scenarios meeting both Dutch TO thresholds remains unchanged, with compliance occurring only when ceiling fans are also included. Notably, scenarios with current construction and a green roof consistently show higher TO-hours than their baseline counterparts. Although the green roof provides a technical improvement, the effect is minimal and likely imperceptible in practice. The reduction in TO-hours is consistent across scenarios, maintaining the same relative ranking of cooling strategies.

The scenario that replicates the baseline setup but includes both a green roof and ceiling fan yields the lowest TO-hours for both the living room and the bedroom.

Terraced

		Baseline				Baseline & Ceiling Fans			
		Single-Sided Ventilation		Cross Ventilation		Single-Sided Ventilation		Cross Ventilation	
		Current Construction Rvalue = 0.15 - 2,50	Renovated Construction Rvalue = 1.70 - 3,50	Current Construction Rvalue = 0.15 - 2,50	Renovated Construction Rvalue = 1.70 - 3,50	Current Construction Rvalue = 0.15 - 2,50	Renovated Construction Rvalue = 1.70 - 3,50	Current Construction Rvalue = 0.15 - 2,50	Renovated Construction Rvalue = 1.70 - 3,50
Night Ventilation from 21:00 - 07:00	Bedroom	1341	1404	1227	1264	1200	1247	1152	1205
	Livingroom	1067	1209	1045	1200	722	1031	713	997
Temperature based Ventilation 15°C < $T_{outside}$ < 27°C	Bedroom	727	761	411	420	453	461	306	311
	Livingroom	243	344	261	302	**87**	**110**	**81**	**105**

Terraced

		Shadings				Shadings & Ceiling Fans			
		Single-Sided Ventilation		Cross Ventilation		Single-Sided Ventilation		Cross Ventilation	
		Current Construction Rvalue = 0.15 - 2,50	Renovated Construction Rvalue = 1.70 - 3,50	Current Construction Rvalue = 0.15 - 2,50	Renovated Construction Rvalue = 1.70 - 3,50	Current Construction Rvalue = 0.15 - 2,50	Renovated Construction Rvalue = 1.70 - 3,50	Current Construction Rvalue = 0.15 - 2,50	Renovated Construction Rvalue = 1.70 - 3,50
Night Ventilation from 21:00 - 07:00	Bedroom	1103	1207	926	1056	777	888	640	728
	Livingroom	546	745	542	719	455	488	457	482
Temperature based Ventilation 15°C < $T_{outside}$ < 27°C	Bedroom	478	452	326	319	316	299	264	244
	Livingroom	**117**	**174**	**108**	**157**	**35**	**47**	**34**	**45**

Terraced

		Green roof				Green roof & Ceiling Fans			
		Single-Sided Ventilation		Cross Ventilation		Single-Sided Ventilation		Cross Ventilation	
		Current Construction Rvalue = 0.15 - 2,50	Renovated Construction Rvalue = 1.70 - 3,50	Current Construction Rvalue = 0.15 - 2,50	Renovated Construction Rvalue = 1.70 - 3,50	Current Construction Rvalue = 0.15 - 2,50	Renovated Construction Rvalue = 1.70 - 3,50	Current Construction Rvalue = 0.15 - 2,50	Renovated Construction Rvalue = 1.70 - 3,50
Night Ventilation from 21:00 - 07:00	Bedroom	1392	1385	1260	1254	1237	1230	1200	1190
	Livingroom	1219	1198	1210	1187	1052	969	1021	941
Temperature based Ventilation 15°C < $T_{outside}$ < 27°C	Bedroom	711	716	401	399	435	434	302	306
	Livingroom	345	327	311	288	**110**	**100**	**105**	**96**

Table 5.3 - TO Exceedance per Situation for the Terraced Residence (Own work, 2025)

The tables present the number of TO hours—defined as the total summer hours during which PMV > 0.5 is exceeded—for each combination of cooling strategies. To ensure consistency across all tables in this thesis, the maximum value for the red color scale is set at 1550 TO hours. This allows for a uniform visual comparison of performance. Values shown in bold blue indicate compliance with Dutch guidelines, meaning that PMV > 0.5 is exceeded for no more than 300 hours, and PMV > 1 is exceeded for no more than 100 hours.

1550 TO Hours

0

X = complience

5.3 Amount of TO Hours for an Apartment

5.3.1 Baseline Performance

Of the 32 baseline scenarios presented in Table 5.4 (top) and the graph in Appendix 5.3, only two meet both Dutch TO-hour compliance thresholds—fewer than 300 hours where PMV > 0.5 and fewer than 100 hours where PMV > 1.0 during the summer period. The remaining scenarios fall significantly short of compliance, with those incorporating night ventilation exceeding the thresholds for more than half of the summer period. Across all cases, temperature-based ventilation consistently results in a lower number of TO-hours compared to night ventilation. Similarly, cross ventilation proves more effective than single-sided ventilation, and current construction types perform better in reducing overheating than their renovated counterparts with higher insulation and improved glazing. Ceiling fans demonstrate a substantial impact, especially when combined with temperature-based ventilation. This combination leads to a more significant reduction in TO-hours than ceiling fans used in conjunction with night ventilation, and when used together with cross ventilation, full compliance with the TO-hour thresholds can be achieved.

Notably, TO-hours are consistently higher in the bedroom than in the living room, despite both rooms being adjacent and sharing similar orientation and exposure to solar radiation and wind. The only differences between the two simulation setups lie in the assumptions for occupant clothing insulation and metabolic rate, which reflect the typical use of each room. In the bedroom, a higher clothing insulation value of 1.5 CLO is applied (to account for bedding and sleepwear), alongside a lower metabolic rate of 0.7 met, representing sleeping activity. In contrast, the living room assumes a clothing insulation of 0.3 CLO (light summer clothing) and a metabolic rate of 1.1 met, typical for activities such as sitting and reading. These input variations may contribute to the observed differences in thermal comfort outcomes.

For both the living room and the bedroom, the most effective scenarios include temperature-based ventilation combined with cross ventilation, either with current or renovated construction, and the use of ceiling fans. However, despite these rooms being adjacent and both employing the most effective strategies, the bedroom still experiences approximately 200 more TO-hours than the living room.

5.3.2 Exterior Solar Shading

In Table 5.4 (bottom) and Appendix 5.3, the same scenarios are shown, this time with exterior solar shading added to the windows. Although the total number of TO-hours is slightly reduced across all cases, the overall order of effectiveness remains unchanged, and no additional scenarios achieve compliance compared to the baseline.

Therefore, the most effective combination for reducing TO-hours in apartments for the solar shading scenario remains the use of ceiling fans alongside temperature based ventilation, current construction and cross ventilation for both the livingroom and bedroom.

5.4 Evaluating Cooling Strategies on the Amount of TO Hours

When comparing the same cooling strategies across the three residential building types, apartment dwellings consistently exhibit the highest number of TO-hours under all simulated conditions, followed by terraced houses and, finally, detached houses. Bedrooms show also higher TO-hours than living rooms, while cross ventilation outperforms single-sided ventilation, and current constructions generally perform better than renovated ones. Several physical and thermal differences between the dwelling types may contribute to these patterns in overheating performance.

One contributing factor is the difference in shape factor between the dwelling types, defined as the ratio between the heat-loss area and the usable floor area. Detached houses generally have a higher shape factor than terraced houses, which in turn exceed that of apartments. A higher shape factor enables buildings—particularly those with low insulation levels—to dissipate internal heat more effectively than more compact dwellings (Hamdy et al., 2022).

Apartment		Baseline				Baseline & Ceiling Fans			
		Single-Sided Ventilation		Cross Ventilation		Single-Sided Ventilation		Cross Ventilation	
		Current Construction Rvalue = 0.15 - 2,50	Renovated Construction Rvalue = 1.70 - 3,50	Current Construction Rvalue = 0.15 - 2,50	Renovated Construction Rvalue = 1.70 - 3,50	Current Construction Rvalue = 0.15 - 2,50	Renovated Construction Rvalue = 1.70 - 3,50	Current Construction Rvalue = 0.15 - 2,50	Renovated Construction Rvalue = 1.70 - 3,50
Night Ventilation from 21:00 - 07:00	Bedroom	1443	1541	1258	1285	1268	1298	1166	1212
	Livingroom	1336	1360	1209	1261	1150	1194	945	1054
Temperature based Ventilation 15°C < $T_{outside}$ < 27°C	Bedroom	813	879	429	443	493	526	300	313
	Livingroom	832	931	293	360	244	270	**110**	**118**

Apartment		Shadings				Shadings & Ceiling Fans			
		Single-Sided Ventilation		Cross Ventilation		Single-Sided Ventilation		Cross Ventilation	
		Current Construction Rvalue = 0.15 - 2,50	Renovated Construction Rvalue = 1.70 - 3,50	Current Construction Rvalue = 0.15 - 2,50	Renovated Construction Rvalue = 1.70 - 3,50	Current Construction Rvalue = 0.15 - 2,50	Renovated Construction Rvalue = 1.70 - 3,50	Current Construction Rvalue = 0.15 - 2,50	Renovated Construction Rvalue = 1.70 - 3,50
Night Ventilation from 21:00 - 07:00	Bedroom	1362	1418	1195	1245	1191	1245	1099	1154
	Livingroom	1271	1303	1116	1189	944	1049	702	822
Temperature based Ventilation 15°C < $T_{outside}$ < 27°C	Bedroom	672	698	379	404	410	434	281	286
	Livingroom	677	741	228	287	186	199	**86**	**91**

Table 5.4 - TO Exceedance per Situation for the Apartment (Own work, 2025)

The tables present the number of TO hours—defined as the total summer hours during which PMV > 0.5 is exceeded—for each combination of cooling strategies. To ensure consistency across all tables in this thesis, the maximum value for the red color scale is set at 1550 TO hours. This allows for a uniform visual comparison of performance. Values shown in bold blue indicate compliance with Dutch guidelines, meaning that PMV > 0.5 is exceeded for no more than 300 hours, and PMV > 1 is exceeded for no more than 100 hours.

1550 TO Hours

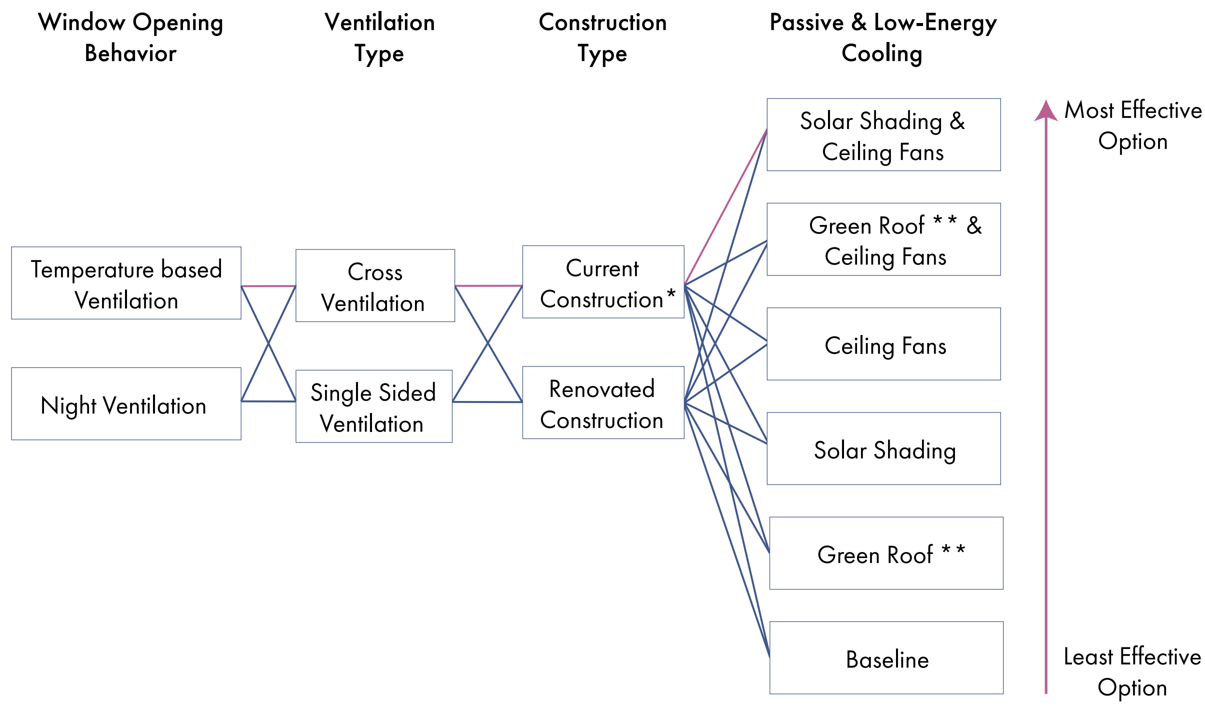
0

X = complience

Another relevant factor is the variation in insulation levels (R-values and glazing type). According to RVO (2023), the detached house model used in this study has the lowest thermal resistance, having been constructed earlier, followed by the apartment and then the terraced dwelling. As noted by several interviewees, lower insulation may allow heat to escape more easily, though theory suggests higher insulation limits heat gains—especially when combined with better glazing. Supporting this view, de Vries et al. (2024) demonstrated that higher R-values, when combined with night or continuous ventilation, can result in fewer TO-hours than poorly insulated alternatives.

In this study, none of the night ventilation strategies resulted in compliance with both Dutch TO-hour thresholds in any of the simulated bedroom scenarios, as no bedroom scenario achieved full compliance. This contrasts with the results reported by de Vries et al. (2024), where similar strategies—applied across various dwelling types with different insulation levels and shading configurations—frequently met comfort standards. A key difference between the two studies lies in the PMV modelling approach for calculating the (G)TO-hours. De Vries et al. used fixed input values for relative humidity (50%), airspeed (0.1 m/s), clothing insulation (0.7 CLO), and metabolic rate (1.2 met), linking the TO threshold directly to a static indoor temperature of 27 °C. In contrast, the simulations in this thesis employed dynamic, hourly varying values for these parameters.

Despite the differences in building types, construction levels, shape factors, and orientation, the results across all simulations show a consistent ranking in the effectiveness of cooling strategies, summarized in Figure 5.1. Temperature-based ventilation always results in lower TO-hours than night ventilation. Cross ventilation is consistently more effective than single-sided ventilation. Current construction performs better than renovated variants with higher insulation and optimized glazing, except for the bedroom scenario's in detached and terraced dwelling. Among passive and low-energy strategies, the most effective combinations are ranked as follows: 1) Solar shading with ceiling fans, 2) Green roofs with ceiling fans, 3) Ceiling fans only, 4) Solar shading only, 5) Green roof only. Thus, the most effective overall combination is: temperature-based ventilation, cross ventilation, current construction, solar shading, and ceiling fans. In contrast, the least effective setup is night ventilation with single-sided ventilation, renovated construction, and no additional passive or low-energy measures (baseline).



= The most effective combination of cooling strategies

** Exceptation for the bedroom scenarios in detached and terraced buildings, where the combination of renovated construction and cross ventilation proves more effective than the current construction variant.*

*** Green roof only applicable to detached and terraced residential buildings.*

Figure 5.1 - Effectiveness Ranking of Cooling Strategies and Their Possible Combinations (Own work, 2025)

5.5 Evaluating Cooling Strategies Beyond Dutch Standards

Interview insights revealed a key limitation of the TO-hour approach: although it incorporates six core factors influencing thermal comfort, it does not account for the timing, duration, or location of exceedances in relation to when and where occupants are actually present. This is particularly relevant, as questionnaire responses indicated that most residents are at home during the night—prioritizing a cool bedroom for sleep—while the living room is primarily occupied during the daytime. Therefore, further investigation into the timing of thermal discomfort in both living room and bedroom is essential to better understand real-world comfort experiences. These temporal patterns are visualized in Figure 5.2 and detailed in Appendices 5.4–5.6, which show that temperature exceedances are not evenly distributed throughout the day and night. Instead, distinct peaks in thermal discomfort are observed during daytime hours for both the living room (left) and bedroom (right) across all combinations of cooling strategies.

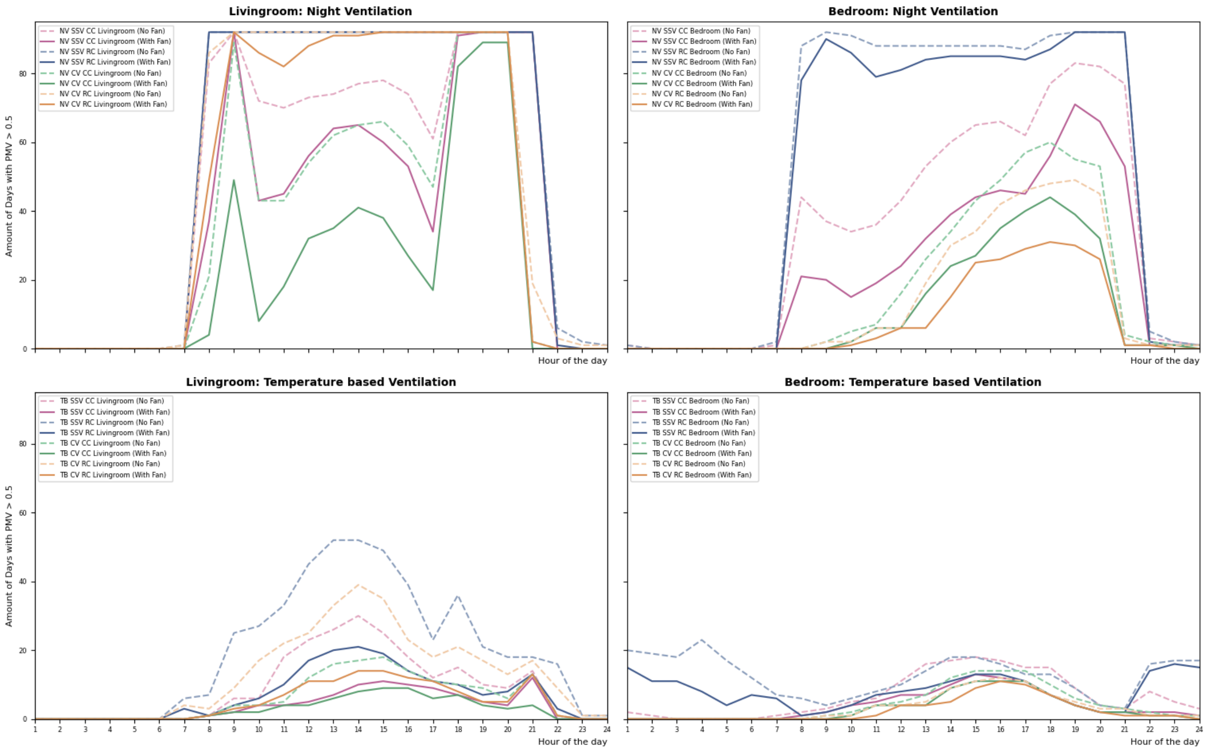


Figure 5.2 - Amount of Days with TO Exceedance (PMV > 0.5) for Each Hour of the Day (Own work, 2025)

Table 5.5 presents three sub-tables showing the number of TO-hours—defined as hours during which PMV > 0.5 is exceeded in summer—for the three residential types: detached, terraced, and apartment dwellings, all using solar shading. Unlike the tables in Sections 5.1 to 5.3, these results consider only the hours during which occupants are assumed to be present in each space. Specifically, occupancy is assumed from 21:00 to 07:00 for the bedroom, and from 07:00 to 21:00 for the living room. These assumptions are based on questionnaire responses and intentionally exaggerated to capture the maximum number of hours per room. The corresponding tables for the baseline and green roof scenarios are provided in Appendices 5.16–5.18.

The most immediate observation is the substantial reduction in TO-hours compared to the full-day scenarios. This is particularly evident in the bedroom scenarios, where night ventilation—defined as continuous ventilation during occupancy hours—results in full compliance across all three residential building types. This occurs even in the baseline scenario, without any additional passive or low-energy cooling strategies applied. Interestingly, none of the bedroom scenarios with temperature-based ventilation achieve the same level of compliance, and they maintain significantly higher TO-hour counts. This contrasts with earlier findings in Tables 5.2–5.4, where temperature-based ventilation consistently resulted in lower TO-hours compared to night ventilation.

Detached

		Shadings				Shadings & Ceiling Fans			
		Single-Sided Ventilation		Cross Ventilation		Single-Sided Ventilation		Cross Ventilation	
		Current Construction *Rvalue = 0.15 - 2,50*	Renovated Construction *Rvalue = 1.70 - 3,50*	Current Construction *Rvalue = 0.15 - 2,50*	Renovated Construction *Rvalue = 1.70 - 3,50*	Current Construction *Rvalue = 0.15 - 2,50*	Renovated Construction *Rvalue = 1.70 - 3,50*	Current Construction *Rvalue = 0.15 - 2,50*	Renovated Construction *Rvalue = 1.70 - 3,50*
Night Ventilation from 21:00 - 07:00	Bedroom	**20**	**31**	**7**	**4**	**8**	**8**	**3**	**2**
	Livingroom	535	1190	370	950	413	910	240	608
Temperature based Ventilation 15°C < $T_{outside}$ < 27°C	Bedroom	**100**	197	**7**	**4**	**52**	175	**3**	**2**
	Livingroom	**50**	172	**46**	136	**24**	89	**17**	**81**

Terraced

		Shadings				Shadings & Ceiling Fans			
		Single-Sided Ventilation		Cross Ventilation		Single-Sided Ventilation		Cross Ventilation	
		Current Construction *Rvalue = 0.15 - 2,50*	Renovated Construction *Rvalue = 1.70 - 3,50*	Current Construction *Rvalue = 0.15 - 2,50*	Renovated Construction *Rvalue = 1.70 - 3,50*	Current Construction *Rvalue = 0.15 - 2,50*	Renovated Construction *Rvalue = 1.70 - 3,50*	Current Construction *Rvalue = 0.15 - 2,50*	Renovated Construction *Rvalue = 1.70 - 3,50*
Night Ventilation from 21:00 - 07:00	Bedroom	**94**	**106**	**33**	**34**	**27**	**29**	**12**	**13**
	Livingroom	546	745	542	719	455	488	457	482
Temperature based Ventilation 15°C < $T_{outside}$ < 27°C	Bedroom	262	267	206	212	201	207	183	185
	Livingroom	**117**	**174**	**108**	**157**	**35**	**47**	**34**	**45**

Apartment

		Shadings				Shadings & Ceiling Fans			
		Single-Sided Ventilation		Cross Ventilation		Single-Sided Ventilation		Cross Ventilation	
		Current Construction *Rvalue = 0.15 - 2,50*	Renovated Construction *Rvalue = 1.70 - 3,50*	Current Construction *Rvalue = 0.15 - 2,50*	Renovated Construction *Rvalue = 1.70 - 3,50*	Current Construction *Rvalue = 0.15 - 2,50*	Renovated Construction *Rvalue = 1.70 - 3,50*	Current Construction *Rvalue = 0.15 - 2,50*	Renovated Construction *Rvalue = 1.70 - 3,50*
Night Ventilation from 21:00 - 07:00	Bedroom	**153**	**196**	**45**	**54**	**40**	**50**	**15**	**17**
	Livingroom	1231	1253	1099	1166	939	1043	701	821
Temperature based Ventilation 15°C < $T_{outside}$ < 27°C	Bedroom	297	307	202	214	210	218	182	183
	Livingroom	613	651	198	209	174	181	**79**	**84**

Figure 5.5 - TO Exceedance for the Detached (top), Terraced (middle) & Apartment (bottom) Buidling with Solar Shading (Own work, 2025)

The tables present the number of TO hours—defined as the total summer hours during which PMV > 0.5 is exceeded—for each combination of cooling strategies for the bedroom during night (21:00-07:00) and the livingroom during the day (07:00-21:00). To ensure consistency across all tables in this thesis, the maximum value for the red color scale is set at 1550 TO hours. This allows for a uniform visual comparison of performance. Values shown in bold blue indicate compliance with Dutch guidelines, meaning that PMV > 0.5 is exceeded for no more than 300 hours, and PMV > 1 is exceeded for no more than 100 hours.

1550 TO Hours
0
X = complience

This difference is further illustrated in Figures 5.3 to 5.5 (Appendices 5.10–5.12 & 5.22-5.24). Figure 5.3 shows the outdoor dry-bulb temperature from the weather file used in the building simulations. Below this graph, two timelines indicate the hourly window opening patterns for both Night Ventilation (NV) and Temperature-based Ventilation (TV) across the entire summer period. The NV timeline reveals a consistent rhythm: windows are open only during nighttime hours and always closed during the day. In contrast, the TV timeline reflects a more dynamic pattern, where windows are opened only when indoor temperatures fall within the predefined comfort range of 25 °C to 27 °C. Outside of this range, the windows remain closed, as shown in the table below the graph.

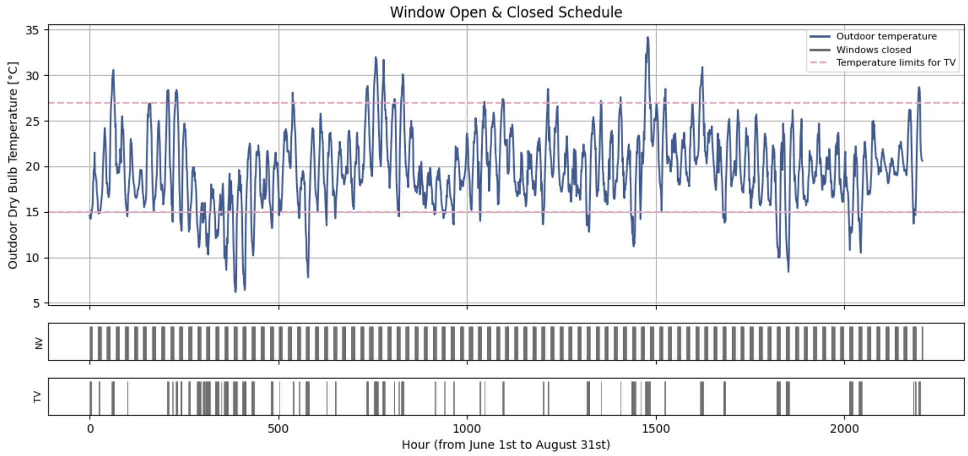


Figure 5.3 - TO Exceedance per Hour during the Night for the Detached Baseline (Own work, 2025)

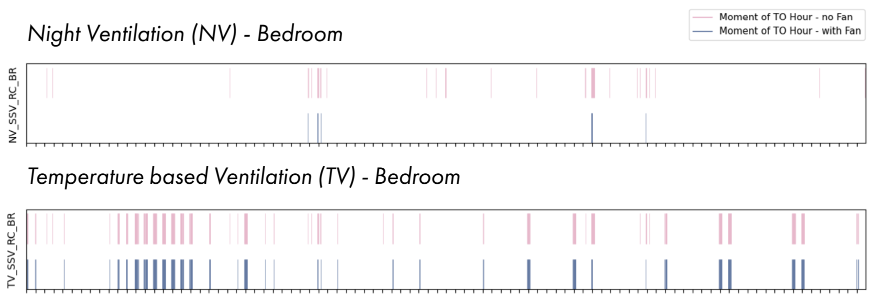


Figure 5.4 - TO Exceedance per Hour during the Night for Detached Residence (baseline bedroom) (Own work, 2025)

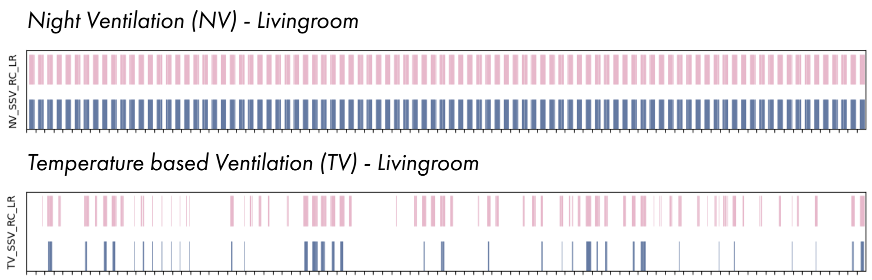


Figure 5.5 - TO Exceedance per Hour during the Day for Detached Residence (baseline livingroom) (Own work, 2025)

Figure 5.4 displays the TO exceedance (PMV > 0.5) during the summer for the bedroom, considering only nighttime hours. Any exceedance occurring during the day is excluded from this figure. In the NV scenario, only a few exceedance hours are observed, occurring precisely when outdoor nighttime temperatures exceed 27 °C. During these moments, opening the windows likely draws warm air indoors, reducing the cooling effect. In the TV scenario—where windows remain closed when temperatures fall below 15 °C or rise above 27 °C—most TO exceedances also occur during these temperature limits. Notably, when outdoor temperatures drop below 15 °C and the windows are closed, TO exceedances also occur, resulting in higher TO-hours for TV than for NV. Additionally, when nighttime temperatures exceed 27 °C, exceedance occurs regardless of whether the windows are open or closed.

Figure 5.5 shows the NV and TV scenarios for the living room during daytime hours, with only TO exceedance (PMV > 0.5) during the day included. In the NV scenario, where windows remain closed during the day, overheating occurs consistently—indicating that keeping the windows closed during occupancy directly results in thermal discomfort. In the TV scenario, TO exceedance still occurs when the windows are closed, particularly when outdoor temperatures rise above 27 °C. However, exceedance is also observed at times when the windows are open, suggesting that other factors—such as solar irradiation or heat transmission—also contribute to overheating.

Keeping the windows continuously open at night in the bedroom results in the lowest exceedance, while temperature-based window operation during the day in the living room proves most effective within typical occupancy patterns. This is preferable occupants are less likely or able to operate windows while asleep at night, whereas during the day they can more easily open or close them as needed. Notably, thermal exceedance increases whenever windows remain closed. Therefore, it may be valuable to explore a scenario in which windows stay open throughout the entire day to determine whether this could further reduce TO exceedance during daytime hours for the livingroom.

5.6 Consecutive TO-Hours and Their Distribution Over the Summer

Now that the extent of TO-hour exceedance during actual occupancy hours in both the bedroom and living room has been established, the effectiveness of cooling strategies can be further evaluated by analyzing the duration and frequency of consecutive exceedance periods. This approach goes beyond the simplified assumption that staying below the legal threshold of 300 TO-hours with PMV > 0.5 automatically guarantees acceptable thermal comfort. If these 300 hours occur consecutively, the perceived effectiveness of a cooling strategy may be significantly lower. Conversely, if exceedances occur only sporadically throughout the day, their impact may be less severe. As noted in the interview with the physiologist in Chapter 4, short periods of mild heat exposure may even be beneficial for health.

Figure 5.6 illustrates the results for the living room of the terraced house under three different configurations: baseline, with solar shading, and with a green roof. The graphs show the frequency of overheating episodes, defined as the number of occurrences of consecutive hours where PMV exceeds 0.5 during the summer. These three configurations were selected for visual comparison due to their contrasting patterns. Corresponding results for the detached and apartment dwellings are provided in Appendices 5.19–5.21. Following this, Figure 5.7 presents the distribution of PMV > 0.5 exceedance across all summer hours (Appendices 5.22–5.24). This allows for comparison between the frequency of continuous exceedance events and their temporal spread—indicating whether overheating is periodically relieved or remains persistent. Together, these figures offer deeper insight into both the intensity and recovery time of thermal discomfort in residential settings.

5.6.1 Consecutive TO Hours

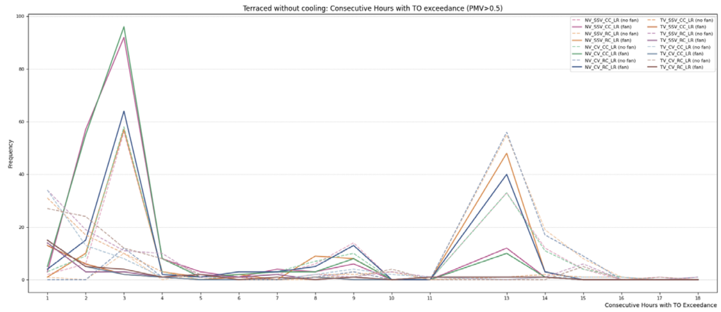
Across all three residential types, the baseline scenarios show two prominent peaks in consecutive TO exceedance: one between 1–5 hours and another between 11–15 hours (Figure 5.6, top). This indicates that these durations are the most frequent lengths of continuous thermal discomfort during summer in the living room.

When comparing fan and non-fan variants (distinguished by solid vs. dashed lines in the graphs), a consistent pattern emerges. Although the same peaks appear in both versions, the frequency of longer overheating events is higher in scenarios without fans. This could be attributed to the fact that non-fan cases generally accumulate more total TO-hours. However, it may also suggest that fans help interrupt overheating sequences earlier by lowering PMV values below the threshold. This interpretation is supported by the increased frequency of shorter overheating events (1–5 hours) in fan scenarios and the corresponding drop in the 11–15 hour range.

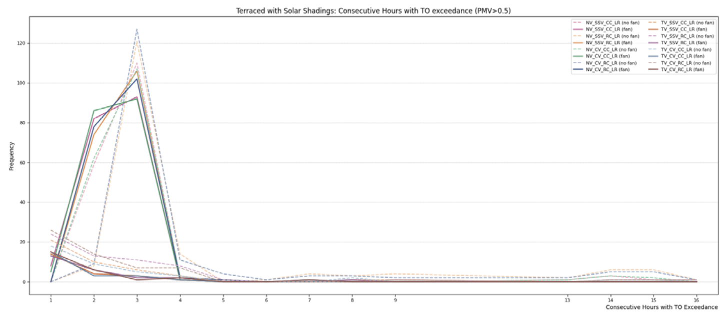
Solar shading also shows a significant effect, particularly in the detached and terraced residences (Figure 5.6, middle). In the detached house, the frequency of 11–15 hour exceedances is nearly halved, while the number of shorter events (1–5 hours) increases. In the terraced residence, the impact is even more pronounced:

overheating sequences longer than 10 hours are almost eliminated, and most TO exceedances are limited to brief periods of 1–4 consecutive hours. This suggests that solar shading not only reduces total overheating but also breaks up longer, more stressful periods into shorter ones. The green roof scenarios show minor improvements over the baseline but are not substantial enough to draw firm conclusions about their impact on consecutive TO exceedance duration (Figure 5.6, bottom).

Terraced Baseline - Livingroom



Terraced with Solar Shading - Livingroom



Terraced with Greenroof - Livingroom

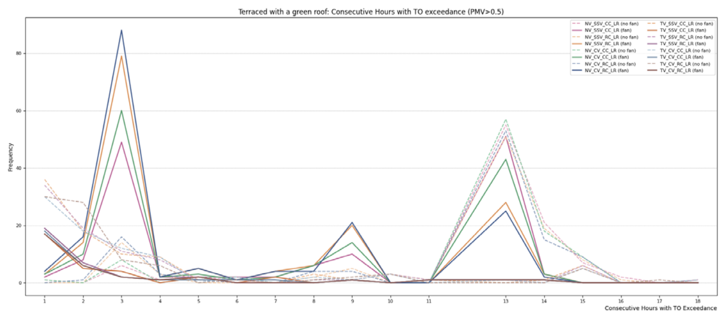


Figure 5.6 - The Frequency of Cosecutive hours where PMV>0.5 for the Terraced Residence (Own work, 2025)

5.6.2 Distribution of TO Hours over the Summer

Although the previous graphs show the frequency of TO exceedance events during the summer period, they do not reveal the duration of the intervals between these overheating episodes. For instance, if high-frequency exceedance periods—such as 14 hours—are broken into smaller sequences with only a single hour of recovery in between, the thermal stress experienced by occupants may still be perceived as uncomfortable. To further examine this, Figure 5.7 displays two scenarios each from the baseline, solar shading, and green roof conditions from the terraced residense, illustrating for every hour of the summer when the PMV > 0.5 threshold is exceeded in the living room.

Notably, the night ventilation scenarios (NV_SSV_CC_LR) for both the baseline and green roof conditions show high levels of TO exceedance. Moreover, the exceedance hours are distributed across the summer and occur in closely spaced intervals. Some short breaks appear between these clusters, often during evening hours—assumed periods when occupants are not using the living room but rather the bedroom and when the windows are considered open. The temperature-based ventilation scenarios (TV_SSV_CC_LR) display fewer overall exceedances. However, when exceedance does occur, it tends to cluster tightly together, resulting in prolonged periods of discomfort. For example, between hour 700 and hour 840 of the simulation, a nearly continuous five-day overheating period is observed in the living room during the day.

The addition of solar shading significantly reduces the duration of prolonged overheating periods. In the baseline scenario, a five-day stretch of continuous exceedance is shortened to approximately two days, with only a few isolated exceedance hours occurring before and after. Solar shading also lowers the intensity of exceedance within those days. When a ceiling fan is included, no full days of overheating remain; any exceedance is limited to a few hours per day—if present at all. A similar pattern is seen in the night ventilation scenarios, where the use of fans further shortens consecutive exceedance periods and increases the time available for thermal recovery between events. The green roof scenario does not show any notable improvement in reducing the number of daily exceedance hours or in shortening the duration of consecutive overheating days.

While night ventilation often leads to full days or repeated episodes of exceedance in the living room, temperature-based ventilation typically results in just some hours per day or short episodes of exceedance. If such short exceedances are considered negligible—supported by the interview of physiologist in Chapter 4, who noted that minor thermal deviations can be harmless or even beneficial—the perceived burden of overheating is greatly reduced. Under this interpretation, the temperature-based ventilation scenario leads to 16 days of exceedance in the baseline case, dropping to 5 with solar shading and to 18 with a green roof of the 92 days in total. With ceiling fans, these numbers further reduce to 7, 2, and 9 days, respectively. While this approach does reduce the total number of TO-hours, it remains insufficient to bring additional scenarios into compliance with the Dutch thresholds, particularly when considering both the total hours exceeding PMV > 0.5 and those exceeding PMV > 1. The Adaptive Thermal Comfort (ATG) method could provide a more tolerant evaluation in such cases, as it accounts for occupants' ability to acclimatize to occasional heat exposure over time. Moreover, the ranking of the most effective cooling strategies for the living room remains unchanged when these additional measurements are considered.

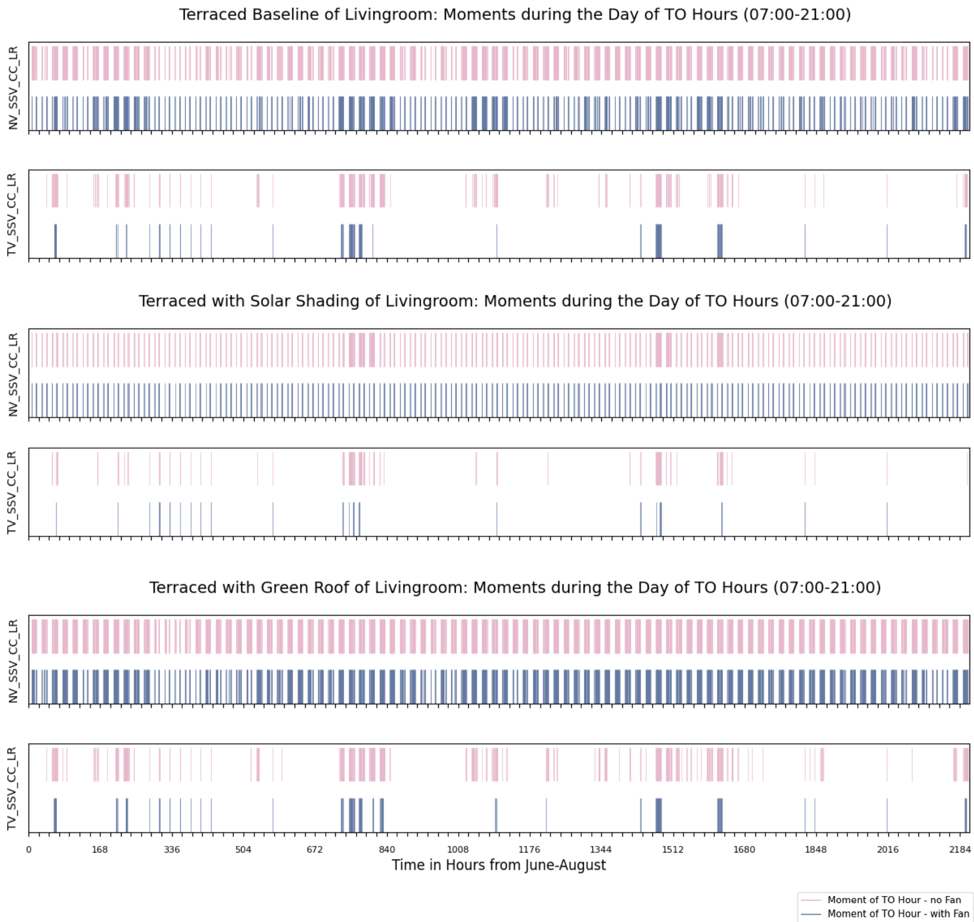


Figure 5.7 - TO Exceedance per Hour of the Summer for Terraced Residence (Own work, 2025)

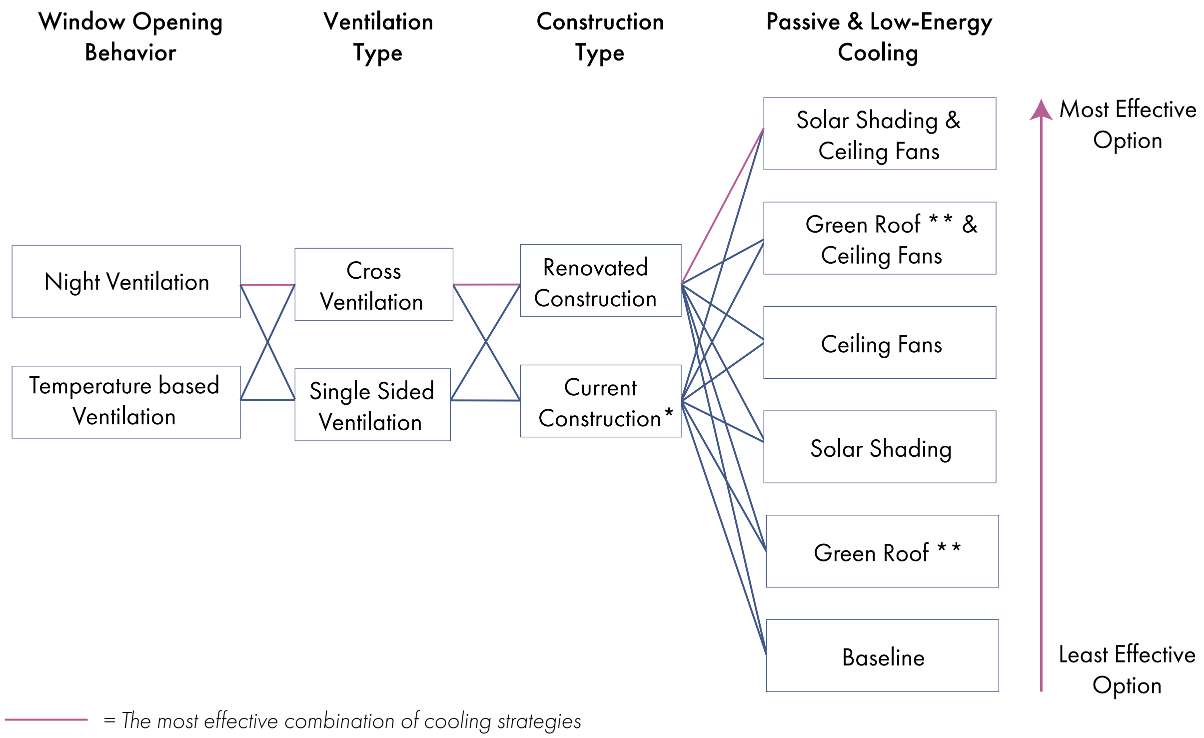
5.7 Ranking Cooling Strategies on Effectiveness

This chapter examined the effectiveness of passive and low-energy cooling strategies across three residential case studies: detached, terraced, and apartment dwellings. Sections 5.1 to 5.3 assessed effectiveness using the Dutch TO-hour guideline, which quantifies the total number of summer hours during which PMV > 0.5 and PMV > 1 are exceeded. Cooling strategy combinations with the lowest number of TO-hours were considered the most effective. However, it is important to note that less effective combinations may still comply with the threshold values set by the guideline

Based on TO Hour assessment outlined in Section 5.1-5.4, both the living room and bedroom, the results showed that temperature-based ventilation consistently led to fewer TO-hours than night ventilation, cross ventilation was more effective than single-sided ventilation, and current construction outperformed renovated construction. Among the passive and low-energy cooling strategies, the combination of solar shading and ceiling fans proved to be the most effective, followed by green roofs with ceiling fans, ceiling fans alone, solar shading alone, green roofs alone, and lastly, no additional cooling strategy.

Section 5.5 and 5.6 focused only on occupancy hours—i.e., when residents are actually present in the space—and excluded short periods of exceedance (mild heat exposure). In this section, the ranking of the most effective cooling strategies for the living room remained the same. However, the results for the bedroom changed. Simulations showed that night ventilation led to fewer TO-hours than temperature-based ventilation, and that renovated construction, when combined with cross ventilation, was more effective than current construction. The ranking of the passive and low-energy strategies, however, remained unchanged.

Figure 5.1 presents the ranking of cooling strategies for the living room, which remains consistent when effectiveness is measured using total TO-hours across the entire summer. Figure 5.8 shows the results for the bedroom, where different outcomes are observed regarding window opening behavior and construction type.



* Exceptation for the bedroom scenarios in the apartment, where the combination of current construction and cross ventilation proves more effective than the renovated construction variant shown in this figure.
** Green roof only applicable to detached and terraced residential buildings.

Figure 5.8 - Effectiveness Ranking of Cooling Strategies and Their Possible Combinations (bedroom) (Own work, 2025)

5.8 Discussion

5.8.1 Summary of Key Findings

This chapter presents insights from dynamic building simulations of three typical Dutch housing types—detached, terraced, and apartment dwellings. The simulations calculate the number of TO-hours, defined as the total summer hours during which the PMV exceeds 0.5, indicating thermal discomfort. Various combinations of passive and low-energy cooling strategies are compared to assess their effectiveness in reducing TO-hours and to answer the sub-question: *What combinations of passive and low-energy cooling strategies are most effective in reducing thermal discomfort across different Dutch housing typologies under future summer climate scenarios?*

Findings following assessing cooling strategies on TO hours

- When cooling strategy effectiveness is evaluated using the TO-hours method, the most effective configuration for both the bedroom and living room involves a combination of strategies: temperature-controlled ventilation (i.e., opening windows based on indoor temperature), cross-ventilation (opening all windows and interior doors), the existing lightweight construction with low R-values, and the addition of solar shading and ceiling fans.
- When comparing the same cooling strategies across the three residential building types, apartment dwellings consistently exhibit the highest number of TO-hours under all simulated conditions, followed by terraced houses and, lastly, detached houses. In all cases, living room scenarios outperform bedroom scenarios when applying the same strategies. Despite these differences in absolute TO-hours, the relative ranking of cooling strategy effectiveness remains consistent across all three dwelling types.
- In the detached residence, where the living room faces south and the bedroom faces north, the living room consistently experiences fewer TO-hours across all tested cooling strategies. This suggests that solar radiation is not the only factor influencing overheating. Differences in clothing insulation, metabolic rate, and floor height may also contribute to the varying comfort levels between rooms.
- In the terraced residence, where both the bedroom and living room face south but the bedroom is located one floor higher, the bedroom consistently shows higher TO-hours. Given the similar solar exposure, this difference is likely due to factors such as metabolic rate, clothing insulation, and vertical positioning within the building.
- In the apartment case, where the living room and bedroom are located adjacent to each other, notable differences still occur in TO-hours. The bedroom consistently shows higher TO-hours, likely driven by differing metabolic rates and clothing insulation levels associated with the room's typical use.
- With this setup, temperature-based ventilation consistently outperforms night ventilation, and cross-ventilation proves more effective than single-sided ventilation. Additionally, current construction generally results in lower TO-hours compared to renovated construction—except in the bedroom scenarios of the detached and terraced dwellings, where renovated construction performs better in combination with cross ventilation.
- Compliance with the thresholds of a maximum of 300 TO-hours (PMV > 0.5) and 100 TO-hours (PMV > 1) is only achieved in terraced houses and apartments when ceiling fans or solar shading are used, either individually or in combination. In detached houses, these thresholds are also met when cross-ventilation is applied.

Findings following assessing cooling strategies beyoncd TO hours

- When only the hours during which residents are assumed to occupy the living room (07:00–21:00) and bedroom (21:00–07:00) are considered in the assessment of TO hours, the most significant changes are observed in the bedroom scenarios. In these cases, all simulations comply with both TO thresholds: 300 TO-hours (PMV > 0.5) and 100 TO-hours (PMV > 1). For the living room, the number of TO-hours does not differ substantially from the full-day assessment, indicating that most exceedances already occur during the assumed occupancy period.
- For the bedroom, the most effective combination of cooling strategies includes: night ventilation (i.e., opening windows only from 21:00–07:00), cross ventilation (opening all windows and interior doors), renovated construction with higher insulation values and improved glazing, and the addition of solar shading and ceiling fans. Notably, applying night ventilation alone—regardless of the construction type

or additional ventilation strategy—always results in compliance with both thresholds across all simulated dwelling types.
- In the living room, the ranking of cooling strategy effectiveness remains consistent with the full-day scenario for all three building types: temperature based ventilation, cross ventilation, current construction, and the addition of solar shading and ceiling fans.
- TO-hours are always observed in both the bedroom and living room when windows remain closed. Exceedances also occur when windows are closed above 27 °C, and in some cases even when windows are open. Below 15 °C, exceedances only occur if windows remain closed.
- Ceiling fans and solar shading significantly reduce the number of consecutive TO-hours when PMV > 0.5, whereas the green roof shows only modest improvements compared to the baseline scenario.
- Based on the interview with the physiologist, short exposures to mild heat are not necessarily harmful and may even benefit occupant health. Therefore, eliminating isolated, short-duration exceedances does not significantly impact overall TO-hour counts or change the relative effectiveness ranking of cooling strategies.

5.8.2 Validation and Consistency with Previous Research

Firstly, the methodology chapter outlined the step-by-step approach used for the building simulations and the collection of required input data. The selection of the three residential typologies was based on the RVO (2023) report, which identifies representative housing types for the broader Dutch building stock. These typologies—detached, terraced, and apartment dwellings—cover approximately 1.2 million of the total 8 million residential buildings in the Netherlands. While each dwelling is unique, the selected models provide a robust representation of overheating potential due to common characteristics such as compactness (shape factor), orientation, and occupant presence throughout the day. Especially the renovated construction variants, with improved insulation and glazing, are likely representative of a wide share of retrofitted Dutch dwellings.

Secondly, although thermal and spatial characteristics may vary slightly across construction years, the consistent ranking of cooling strategy effectiveness across all three dwelling types enhances the generalisability of the results. The simulation framework was designed to be adaptable; with adjusted building geometry and a location-specific EPW file, it can be applied to a wide range of projects and regions.

Thirdly, metabolic rate and clothing insulation—unlike indoor air temperature, radiant temperature, relative humidity, and airspeed—were not dynamically simulated but instead derived from the questionnaire results. The reported metabolic rates were consistent with assumptions from studies by de Vries et al. (2024), Alders et al. (2024; 2025), and Huizenga et al. (2023), which assume low-activity behaviours indoors (e.g., sitting or standing). However, the clothing insulation values reported in this study were significantly lower than in previous studies, as occupants reported wearing minimal clothing at home due to the absence of dress codes. These values were used as assumptions in the simulations and may particularly influence the results for the living room. For the bedroom, lower metabolic rates for sleeping and higher clothing insulation—due to pyjamas, bedding, and summer blankets—were applied, providing a more behaviourally accurate representation.

Another consideration involves the differences in modelling assumptions compared to previous research. For example, while some earlier studies concluded that renovated dwellings consistently exhibited lower overheating levels, this study did not observe that trend across all scenarios. The reasons for these differences remain unclear, and no definitive conclusion can be drawn about which findings more accurately reflect real-world performance.

Moreover, the climate data used in the simulations also impacts the outcomes. This study applied future weather scenarios based on EPW files developed by Heiranipour et al. (2024), which align with KNMI projections from Bessembinder et al. (2023). While these projections are academically justified, the actual severity of future summer climates remains uncertain. Shifts in temperature or humidity levels could impact both the total number of TO-hours and the effectiveness of various cooling strategies. For example, if future summers are milder or more extreme than expected, occupant behaviour and ventilation patterns may change—potentially influencing compliance with comfort thresholds and even the relative ranking of different strategies.

In terms of evaluation methodology, although the adaptive comfort model (e.g., ATG) is widely considered more suitable for naturally ventilated buildings—due to its wider comfort thresholds and behavioural flexibility—this study deliberately used the TO-hour method. This decision aligns with current Dutch regulations and maintains a direct, quantifiable link to PMV-based metrics, which remain dominant in retrofit assessments. Furthermore, the adaptive model assumes consistent behavioural adjustments (e.g., opening windows, adjusting clothing), an assumption that was not supported by this study's interview and questionnaire results especially not in the bedroom scenario´s where adaptation is limited.

In contrast, the PMV-based TO-hour method provides a conservative estimate of thermal discomfort and functions as a worst-case scenario. Adaptive behaviours—such as reduced activity, lighter clothing, natural ventilation, ceiling fans, and solar shading—were incorporated into the simulation inputs rather than reflected through broader adaptive thresholds. The only aspect not captured was the physiological and psychological adaptability of occupants to naturally ventilated spaces. As such, the TO-hour estimates may slightly overstate thermal discomfort, as occupants might perceive conditions as more comfortable in practice.

Additionally, while the GTO (Weighted Temperature Exceedance) metric considers the severity of discomfort by assigning weights to PMV exceedances, its output is more complex to interpret since the number of GTO-hours can surpass the actual number of occupied hours. To mitigate this, this study distinguishes between TO-hours where PMV exceeds 0.5 (indicating discomfort) and PMV exceeds 1.0 (indicating potential health risk). Although the strategy rankings are based on PMV > 0.5, it is important to note that a strategy which significantly reduces PMV > 1.0 could have a greater impact on GTO than TO—potentially altering the perceived effectiveness of cooling strategies. For this reason, Appendices 5.7–5.9 and 5.13–5.15 include visualisations of both PMV thresholds.

Lastly, internal consistency checks were used to validate the robustness of the simulation outcomes. TO-hour counts per scenario were compared, and SET* distributions were analysed using boxplots (see Appendices 5.25–5.27). These outputs demonstrated logical and consistent patterns, strengthening confidence in the reliability and validity of the results.

5.8.3 Interpretation of Results

The simulation results show a consistent pattern across all dwelling types: detached houses experience the lowest number of TO hours, followed by terraced houses, with apartments consistently displaying the highest overheating risk. This trend aligns with findings by Humdy et al., who attribute this to differences in thermal mass, façade surface area, and internal zoning. Detached dwellings typically have larger interior volumes and more exterior façade area, which slows down internal temperature rise and allows for better passive heat dissipation. In contrast, apartment units often consist of compact, enclosed spaces with limited exposure to external walls, leading to faster and more intense overheating accumulation during warm periods.

Solar shading proved to be more effective in detached and terraced dwellings than in apartments. This can be explained by the architectural configurations described in the RVO (2023) report: many apartments feature covered balconies or galleries, which already provide fixed external shading above the window surfaces. As a result, the added impact of dynamic solar shading is more limited compared to the other case studies, where façades are fully exposed and more responsive to shading interventions. Despite these differences in absolute overheating reduction, the relative ranking and proportional effectiveness of cooling strategies remain largely consistent across all building types.

Across the simulations, several scenarios achieved compliance with the proposed overheating thresholds: a maximum of 300 TO hours for PMV > 0.5, and 100 TO hours for PMV > 1. While these thresholds provide a regulatory benchmark, they do not necessarily reflect perceived thermal comfort. In several cases, PMV exceedances occurred in prolonged sequences during daytime hours or consecutive warm days. Even when thresholds are not exceeded, clustering of discomfort periods may still be perceived as highly intolerable. In contrast, air conditioning can eliminate nearly all discomfort hours, by drastically reducing temperature levels. This may explain why, despite regulatory compliance, passive strategies could still be perceived as insufficient by some residents—especially in comparison to the immediate relief offered by active cooling.

Moreover, the simulations isolating occupied hours in bedrooms (21:00–07:00) demonstrated that night ventilation alone—regardless of dwelling type, construction standard, or additional cooling measures—was sufficient to achieve compliance with both TO thresholds. While this outcome suggests that a simple behavioural intervention could be effective in mitigating future overheating risks, it should not be misinterpreted as a complete solution. If night ventilation were truly sufficient under future climate conditions, current overheating concerns would already be negligible—yet this is demonstrably not the case. Although the bedroom scenarios remain compliant with Dutch TO thresholds, the presence of over 100 TO-hours indicates a potential for thermal discomfort, particularly when exceedances cluster during heat events. Additionally, since occupants generally prefer lower temperatures in bedrooms compared to living rooms (de Vries et al., 2024), the standard discomfort threshold of PMV > 0.5—typically applied uniformly—may not accurately reflect perceived comfort in sleeping environments. This suggests that even lower PMV thresholds might be more appropriate for evaluating bedroom comfort, highlighting the need for differentiated comfort criteria based on room function.

For living rooms, simulations focused on daytime hours (07:00–21:00) confirmed that temperature-based ventilation—where windows are opened only when indoor temperatures are between 15°C and 27°C—is among the most effective and practical strategies. This aligns well with occupancy patterns, as residents are typically awake and able to manually operate windows during these hours, unlike at night. However, an analysis of TO-hour exceedances in relation to window status revealed that thermal discomfort is consistently recorded when windows remain closed—even when indoor temperatures drop below 15°C. In such cases, the lack of ventilation leads to an accumulation of indoor heat and an increase in PMV values and therefor in TO hours.

Finally, it is important to note that the results are based on the continuous application of the behaviours associated with each cooling strategy combination. This means that when one set of actions is implemented, its effect is measured in isolation, without immediately switching to or combining it with others in response to changing conditions. This is particularly relevant for natural ventilation and solar shading, where both the onset and dissipation of their cooling effect take time. A delay in applying these strategies can lead to increased overheating, which does not dissipate instantly once the strategy is activated. Only ceiling fans and, to some extent, cross ventilation (due to the direct sensation of air movement) can provide immediate relief, as their effect is not dependent on lowering room temperature, but rather on increasing perceived comfort through elevated airspeed. In contrast, strategies like green roofs and insulation upgrades involve fixed physical modifications and cannot be easily applied or removed without substantial retrofitting.

5.8.4 Practical Implications

First and foremost, a key practical insight from this study is that ceiling fans, even when used as a standalone intervention, consistently outperform solar shading and green roofs in reducing TO hours and achieving compliance with Dutch overheating thresholds. This highlights their potential as a highly scalable and effective solution for improving thermal comfort in existing dwellings under future summer conditions.

In addition, ceiling fans offer several practical advantages. They are relatively low-cost, require no professional installation, and typically do not need permits or landlord approval. As such, they can be implemented by both homeowners and tenants—an accessibility confirmed during interviews with representatives from the national housing association and a major housing corporation.

Moreover, ceiling fans offer immediate perceptual relief by enhancing indoor airspeed, which improves thermal comfort without necessarily lowering room temperature. In contrast, measures such as solar shading or window operation are often deployed reactively—after overheating has occurred—thereby limiting their effectiveness. These characteristics make ceiling fans a strong low-energy alternative to air conditioning, particularly in the absence of major retrofits or regulatory enforcement.

Beyond individual strategies, the simulation results provide a clear and actionable hierarchy of effective interventions. When single-sided ventilation proves inadequate, cross-ventilation should be considered the next step. If windows cannot remain open throughout the day, ensuring timely window operation—particularly during occupancy—becomes critical to avoid internal heat build-up. If envelope measures like green roofs or shading alone prove insufficient, ceiling fans can be used to significantly enhance comfort. Interestingly, insulation showed limited impact on summer performance, suggesting it should primarily be optimised for winter comfort—provided that sufficient ventilation is ensured during summer.

Looking ahead, the findings support the case for expanding energy label schemes to include indicators for summer performance. While current labels primarily assess winter-related efficiency—based on insulation quality, glazing type, and heating systems—a parallel framework could evaluate a dwelling's capacity for summer resilience. Criteria could include natural ventilation potential (e.g., operable windows), and the presence of passive or low-energy cooling infrastructure such as solar shading, green roofs, or ceiling fans. Although behavioural factors cannot be directly included in the rating, the availability of such infrastructure does enable occupants to act—and should therefore be factored into housing quality assessments.

However, integrating these measures into regulatory systems is not without challenges. Unlike insulation or glazing, interventions like solar shading and ceiling fans are often demountable and user-dependent, making them less reliable as fixed building assets. Their effectiveness hinges not only on presence but also on correct and consistent use—factors that current energy labels do not account for. If regulatory frameworks fail to acknowledge the value of these low-energy alternatives, the continued rise in air conditioner adoption—as noted by Rovers (2023)—is likely to accelerate. This would ultimately necessitate even stricter CO_2 and energy-reduction policies in the future, to compensate for emissions that could have been prevented through more proactive guidance and incentive schemes today.

5.8.5 Limitations

As with previous studies on overheating in Dutch dwellings, this research focused solely on the number of hours with excessive heat exposure (TO hours), without accounting for instances in which occupants may experience cold discomfort during summer. Boxplots in Appendices 5.25–5.27 illustrate that the SET* temperature frequently drops below 15°C, indicating that cold discomfort may also occur. In reality, occupants could respond by closing windows, adding layers of clothing, or retracting solar shading—behavioural adaptations that could, in turn, influence indoor temperature dynamics. However, this study does not treat low temperatures as thermal discomfort events, as the TO-hour method accounts only for overheating, not cold stress.

Another limitation concerns the assumptions made about occupant behaviour during night hours. Specifically, the temperature-based ventilation strategy assumes that windows are actively opened or closed based on temperature thresholds, even while occupants are asleep. This behaviour is unlikely in practice. In contrast, the night ventilation scenario assumes windows remain open throughout the night, which is more reflective of actual routines (e.g., opening windows before bedtime and leaving them open). As a result, the model shows night ventilation outperforming temperature-based ventilation in reducing overheating during sleeping hours, although both strategies may result in similar outcomes in practice.

Moreover, behavioural assumptions within the simulations were simplified. Temperature-based ventilation assumes all windows operate simultaneously, and cross-ventilation presumes that all internal doors in the building are open. In reality, residents may ventilate only specific rooms, and interior doors may remain closed. Furthermore, the same ventilation behaviour was applied uniformly across the entire dwelling, instead of modelling distinct routines for individual rooms (e.g., bedroom vs. living room). This may have led to an overgeneralisation of results and missed opportunities to identify more nuanced combinations of strategies.

Besides that, the simulations used an EPW weather file based on a projected 2050 climate scenario for De Bilt, the location of the Dutch national weather station. While De Bilt provides consistent national data, it is a relatively green and suburban area. Consequently, this model likely underestimates the Urban Heat Island (UHI) effect present in dense urban environments, where outdoor temperatures can rise 3–5°C higher than surrounding areas (de Vries et al., 2023). Incorporating UHI-adjusted climate files could significantly elevate indoor temperatures and may alter conclusions regarding overheating thresholds and strategy effectiveness.

Finally, this study employed the Predicted Mean Vote (PMV) model to evaluate thermal comfort, which is based on an average thermal sensation for healthy group of people. This limits its relevance for vulnerable populations such as elderly individuals, young children, or those with chronic health conditions, who are more sensitive to heat stress. Since these groups were not specifically targeted in this study, the conclusions may underestimate overheating risks for those most at risk.

5.8.6 Recommendations for Future Research

Future research should further explore the effectiveness of passive and low-energy cooling strategies under the limitations discussed above, particularly by simulating more extreme urban heat island (UHI) scenarios or future heatwave conditions. These situations, in which outdoor temperatures frequently exceed 27°C, are likely to result in windows remaining closed—an outcome that, in this study, consistently led to immediate TO-hour exceedances indoors. This suggests that alternative behavioural patterns or combinations of strategies may become more effective under such conditions. It is also important to consider that ceiling fans, while highly effective in moderate conditions, may become less beneficial—or even harmful—in hot and humid environments, as they can increase the risk of heat strain when both operative temperature and relative humidity are elevated.

In addition to building simulations, testing cooling strategies in real homes is highly recommended. The thermal comfort models most often used—PMV and the adaptive model—were developed in the 1980s. These models may not fully reflect how people in the Netherlands experience indoor heat today, especially now that summers are getting noticeably warmer due to climate change. Field studies could help test whether these older models still apply in today's housing stock within the Dutch context and usual behavioral patterns. Another useful direction for future research would be to compare how people experience thermal comfort in different rooms—such as the living room versus the bedroom—even when indoor temperatures are the same. This could reveal whether certain rooms, like bedrooms, need extra or different types of cooling to feel equally comfortable. These insights would help in developing more targeted design strategies for different spaces in the home.

Moreover, interviews and questionnaire results revealed that thermal comfort is not the sole criterion guiding the adoption of cooling strategies. For residents, affordability, low environmental impact, and energy efficiency are key priorities. For designers and developers, additional concerns include low investment costs, ease of installation, and minimal maintenance. Future research should therefore rank cooling strategies not only by thermal performance but also according to these broader evaluation criteria. This would enable direct comparison with conventional mechanical cooling systems such as air conditioners, allowing different user groups to identify which solutions best align with their needs and constraints. Such a multi-criteria decision-making framework would enhance the practical applicability of passive and hybrid cooling solutions across the housing sector.

6. Conclusion

6. Conclusion

As climate change increases the intensity and frequency of heat events, Dutch households are turning more frequently to energy-intensive solutions like air conditioning. This study shows that passive and low-energy strategies—when applied in the right combinations and at the right moments—can substantially reduce overheating in detached, terraced, and apartment dwellings in the Netherlands. By combining stakeholder interviews, a resident questionnaire, and dynamic thermal simulations, the results offer insight into both the technical effectiveness and the practical feasibility of these strategies.

First, both interviewees and residents consistently indicated that winter comfort remains a higher priority than summer comfort, as it has a more direct impact on CO_2 reduction, energy consumption, and household energy bills. As a result, renovations aimed at improving winter performance—such as enhanced insulation or high-performance glazing—are typically preferred. Moreover, residents emphasized that effective cooling strategies should not only provide thermal comfort but also minimize energy use, financial costs, and environmental impact. In contrast, professionals such as designers and developers prioritized low investment costs and minimal maintenance. These findings suggest that the most technically effective measures for maintaining thermal comfort are not always perceived as the most feasible or desirable in practice, revealing a gap between technical potential and real-world implementation. Future research could address this gap by developing an integrated ranking framework for cooling strategies—building on the thermal performance assessed in this study, but also incorporating the practical, financial, and environmental criteria identified by stakeholders.

Second, the building simulations show that every tested combination of passive and low-energy cooling strategies reduces the number of TO hours—defined as the hours during which PMV > 0.5 is exceeded in summer—compared to the baseline scenario, indicating improved thermal comfort across all dwelling types. Detached homes experienced the lowest levels of overheating, followed by terraced houses and apartment dwellings. Although the absolute overheating values differ, the relative ranking of cooling strategies remains consistent across typologies. According to measurements as TO hours, the most effective combination of strategies for both living rooms and bedrooms includes: temperature-based ventilation (windows open when indoor temperatures are between 15–27°C), cross-ventilation (all windows and interior doors open), current lightweight construction with low insulation values, and the addition of both solar shading and ceiling fans. Additionally, simulations show that temperature-based ventilation consistently outperforms night ventilation; current construction outperforms renovated construction in summer; and cross-ventilation is more effective than single-sided ventilation. Among individual measures, ceiling fans alone most significantly reduce TO hours, outperforming both solar shading and green roofs alone.

Third, when thermal discomfort is assessed only during the occupancy hours of each room, the total number of TO hours decreases in both living rooms and bedrooms. In bedrooms, the use of night ventilation alone—when combined with any other cooling strategy—is sufficient to meet the Dutch thresholds of 300 TO hours (PMV > 0.5) and 100 TO hours (PMV > 1.0). While the effectiveness ranking in living rooms remains unchanged, it shifts in the bedroom: the most effective configuration includes night ventilation (windows continuously open at night), cross-ventilation, renovated construction with higher insulation and optimized glazing, and the addition of both ceiling fans and solar shading. Again, ceiling fans as a standalone measure outperform other passive cooling strategies in this context.

Finally, with regard to the duration and clustering of thermal discomfort, ceiling fans and solar shading were found to significantly reduce consecutive overheating hours and multi-day heat exposure, even when total TO hours remained above regulatory thresholds. Although some interviewees suggested that brief exposure to moderate heat may offer health benefits for the general population, this was not explored in the resident questionnaire, nor did it prompt any reconsideration of the official TO-hour thresholds. Importantly, these perceptions did not influence the relative effectiveness ranking of cooling strategies.

This thesis demonstrates that passive and low-energy cooling strategies can effectively enhance heat resilience in existing residential buildings in the Netherlands during summer periods under future climate conditions.

When applied in the right combinations and aligned with daily routines, these measures offer a practical and energy-efficient alternative to air conditioning. However, their success depends on more than technical performance alone. To accelerate adoption, a shift is needed—from the current focus on winter performance and newly built housing—to a proactive approach that addresses summer comfort in the existing housing stock. This requires integrated policy measures, including updated energy labels that reflect cooling potential, financial incentives for low-energy solutions, and public engagement to raise awareness and encourage behavioural change. Only through such a systemic approach can passive cooling evolve from a promising technical option, as demonstrated in this thesis, into a widely adopted and effective mainstream practice.

7. Reflection

7. Reflection

During my Bachelor in Architecture, I vividly remember a project where we had to renovate a large residential building. I worked hard to integrate technical solutions that would ensure residents could continue to live there for many years. I received a 7. Another student received an 8.5 — even though their design had no windows in the bedrooms. That moment made me reflect on what on architectural design could receive high grates but had in my opinion no change to become a real project because its technical lack of no windows in the bedroom. Beyond solid structures and beautiful facades, it is ultimately the comfort and well-being of the people inside that counts the most. This realization strongly resonated with the presentation by Alessandra Luna Navarro, who spoke about simulating buildings for thermal comfort, and the complexity of applying these principles in real-world projects. Even though this topic had not been a major part of my Bachelor or Master curriculum, I was immediately motivated to follow this graduation project.

Graduation Process

Since the topic was still unfamiliar and not yet clearly defined, the first few months mainly consisted of extensive reading, writing, crossing things out, and trying to identify a relevant knowledge gap. This was by far the most challenging part of the entire process. I didn't know what to expect, nor what I would be capable of achieving within the time frame of the thesis. Fortunately, the bi-weekly meetings with Alessandra, Valerio, and Lorenzo from Buro Happold helped steer me in the right direction — although at times, they also opened up new directions that pulled me further away from the original topic. Around the time of the P2 deadline, the stress really started to build. Until just a few weeks before, I felt like I had no clear direction, and I hadn't yet started working at Buro Happold, where I would later benefit from more focused feedback and sparring.

Looking back, it felt like I said "yes" to everything during that period:
– Can you run simulations? Yes.
– Maybe also conduct interviews? Of course.
– Process the results in Python? Sure.
– Reach residents via a questionnaire? Absolutely.

It was during the TU Delft holiday break that I truly felt my thesis began. I started working at Buro Happold and spent full days at the office, determined to live up to everything I had committed to. And fortunately — I enjoyed it. I still remember the hours spent with Valerio troubleshooting a Honeybee error, and the expert interviews that not only provided valuable insights but also taught me a great deal beyond the scope of the research. Where I initially thought of a thesis as a way to deepen existing knowledge, for me it became a real expansion — of both skills and understanding. I ended up doing things I never thought I was capable of.

This learning curve was also reflected in the content of my research. With each interview, I discovered a new layer or nuance that I wanted to incorporate into my simulations. Rather than simply developing the concept I had presented during my P2, I began questioning many of the assumptions found in previous literature. As a result, my findings started to diverge slightly from what the literature had suggested — and this made it feel like I was truly conducting research. Looking back, I would advise myself to define a clearer direction earlier on. Start modeling sooner, conduct an initial interview — because it's in those early, concrete steps that you encounter the overlooked aspects, and identify where you can make a real impact. By approaching the project with enthusiasm, I noticed that this energy became contagious. Several of the experts I interviewed later emailed me back with questions about my approach, which allowed me to share some of the knowledge I had acquired with them. This was something I had not expected, but it gave me an incredible amount of motivation to finish the project in the best way possible.

One aspect I struggled to fully grasp and where I would have benefited from more guidance from my supervisors was the design component. In my experience, I addressed various design aspects of a dwelling across three case studies, evaluating how specific cooling strategies mitigate overheating. However, I did not visually represent design elements such as window placement or ceiling fan positioning in my final outcomes. While this may have been justified given the technical orientation of the study, I now wonder whether I missed an important opportunity by not incorporating these elements more explicitly. Perhaps I leaned too heavily into the technical side of the thesis. In hindsight, I would have appreciated clearer direction on how to incorporate the design aspect more effectively, especially since this turned out to be one of my weaker areas in the project.

What this thesis has taught me above all is that there are no real limits to what you can learn — especially when you're open to trying new things. Saying "yes" to unfamiliar software and new methods turned out to be one of the most valuable choices I made, and it allowed me to enjoy the process much more than I expected. At the same time, it was also a vulnerable and uncertain journey. Presenting new insights to my supervisors every two weeks often felt exposing — especially when something I had worked very hard on didn't deliver the results I had hoped for. In the beginning, I would enter these meetings feeling quite nervous. But over time, that has changed. I've grown more confident in how I present and discuss my work, and I see that personal development as an important part of this experience — one that evolved quietly in the background.

Sociatal impact

As outlined above, all the cooling strategies assessed in this study are technically feasible in existing residential buildings, provided that necessary approvals—such as permits or consent from homeowner associations (VvEs)—are obtained for external modifications like solar shading, double glazing, or green roofs. One of the most impactful findings in the Dutch context is that, according to the building simulations, ceiling fans are the most effective single strategy for reducing overheating, outperforming solar shading and green roofs. While ceiling fans are already common in many other countries, this evidence-based outcome could serve as a catalyst to introduce them more widely in Dutch homes, offering a low-energy alternative to air conditioning—especially in situations where passive cooling strategies alone do not sufficiently reduce discomfort.

By demonstrating the effectiveness of passive and low-energy solutions across a range of scenarios, this project contributes meaningfully to the goals of sustainable development. In particular, it highlights that indoor thermal comfort can be achieved without relying solely on energy-intensive systems like air conditioning. Moreover, these strategies do not compromise thermal comfort during winter months, thereby supporting year-round energy efficiency and contributing to both CO_2 reduction and lower energy consumption.

Importantly, the inclusion of stakeholder interviews and resident questionnaires revealed that comfort is not the only driver behind the adoption of cooling strategies. Factors such as investment cost, environmental impact, ease of maintenance, and visual acceptability also play a significant role in decision-making. This makes the project not only an extension of the technical knowledge on cooling effectiveness, but also an entry point into understanding the broader social and behavioural dimensions that influence implementation. These insights are critical if passive and low-energy strategies are to be considered more seriously—and potentially even prioritized—over conventional air conditioning systems in future housing upgrades.

While solar shading, green roofs, and improved insulation are frequently mentioned in interviews and literature as effective methods for reducing heat gain, they often require invasive installation, high upfront costs, and ongoing maintenance. Moreover, these measures can significantly alter the architectural expression of a building. In contrast, strategies like cross-ventilation—achieved by opening all windows and internal doors—and ceiling fans offer effective cooling without changing the building's exterior. Ceiling fans, in particular, do not require permits, are easy to install, and can be operated immediately when needed. One potential barrier, however, could be aesthetic resistance to their presence in interior spaces, which may limit acceptance among certain users. Addressing such perceptual barriers could further support their wider adoption in the Dutch housing context.

This process, as expected, has been full of ups and downs — but always with a clear upward trajectory. It has been incredibly rewarding to experience that, in your final year, you get one last opportunity to truly demonstrate what you're capable of. What also stood out was the shift in perspective: for once, I was not only learning from others, but also had the chance to share knowledge myself — to be regarded, even briefly, as an "expert" on a specific topic. That was a new experience for me, and a surprisingly enjoyable one.

Looking back, I do so with a strong sense of pride and gratitude — and with an even stronger aversion to air conditioners, which I hope to convey during my final presentation. I'm excited to present this work, and I look forward — with anticipation — to closing this chapter and receiving the red diploma tube.

8. References

Alders, N., Hofman, M., Lenzholzer, S., Pijpers, M., Kluck, J., Boerstra, A., & Rooijakkers, E. (2025). ISSO-rapport 110820 Integraal Ontwerpen voor Zomercomfort.

Alders, N., te Kulve, M., Vis, I., Kemperman, R., van de Winkel, F., van der Horst, S., van Marken Lichtenbelt, W., Kurvers, S., Loomans, M., Kuijer, L., Bokel, R., & Versteeg, B. (2024). ISSO-publicatie 74 Thermische behaaglijkheid. In 74. ISSO.

Bessembinder, J., Bintanja, R., van Dorland, R., Homan, C., Overbeek, B., Selten, F., & Siegmund, P. (2023). KNMI'23 klimaat scenario's. www.knmi.nl/klimaatscenarios

Chu, C. R. (2023). Assessment of year-round wind-driven ventilation by an integrated ventilation model. Building and Environment, 243. https://doi.org/10.1016/j.buildenv.2023.110710

Cui, Y., Shinoda, J., Bogatu, D.-I., Olesen, B. W., & Kazanci, O. B. (2023). Heat Stress Indicators in Certification Schemes for the Built Environment.

de Dear, R., & Brager, G. S. (1998). Developing an adaptive model of thermal comfort and preference. UC Berkeley: Center for the Built Environment. https://escholarship.org/uc/item/4qq2p9c6

Duurzaam Gebouw. (2022, September 1). Klimaatmissie: aan de slag gaan met Ladder van Koeling.

DW Planet A. (2023, August 4). How to cool our homes (even without ACs).

European Commission. (2003). Indoor air pollution: new EU research reveals higher risks than previously thought. IP/03/1278. https://ec.europa.eu/commission/presscorner/detail/en/ip_03_1278

European Commission. (2020, October 14). Renovation Wave: doubling the renovation rate to cut emissions, boost recovery and reduce energy poverty. https://ec.europa.eu/commission/presscorner/detail/en/ip_20_1835

European Environment Agency (EEA). (2024). The impacts of heat on health: surveillance and preparedness in Europe. https://www.eea.europa.eu/en/analysis/publications/the-impacts-of-heat-on-health

eurostat. (2024). Heating and cooling degree days -statistics. https://ec.europa.eu/eurostat/statisticsexplained/

Fanger, P. (1970). Thermal comfort, Kopenhagen: Danish Technical Press, 1970. Danish Technical Press.

Gassert, f, Cornejo, E., & Nilson, E. (2021). Making Climate Data Accessible: Methods for Producing NEX-GDDP and LOCA Downscaled Climate Indicators. In Technical Note. DC: World Resources Institute. https://www.wri.org/research/making-climate-data-accessible. www.resourcewatch.org

Hamdy, M., Carlucci, S., Hoes, P. J., & Hensen, J. L. M. (2017). The impact of climate change on the overheating risk in dwellings—A Dutch case study. Building and Environment, 122, 307–323. https://doi.org/10.1016/j.buildenv.2017.06.031

Heiranipour, M., Favoino, F., Juaristi Gutierrez, M., & Avesani, S. (2024). Typical and Extreme (Heatwave) Future Weather Files for Building Energy Simulations: Case Studies for Turin and Bolzano, Italy, and De Bilt, Netherlands. Zenodo. https://doi.org/10.5281/zenodo.14274362

Huizenga, C., Zhang, H., Schiavon, S., Kwong, L., Brager, G., Arens, E., Duarte Roa, C., Exss, K., Luna Navarro, A., & More Authors. (2024). Establishing Maximum Safe Indoor Temperatures for U.S. Residential Buildings. Comfort At The Extremes. https://www.researchgate.net/Publication/387666278

Keith, L., Meerow, S., & Wagner, T. (2019). Planning for Extreme Heat: A Review. Journal of Extreme Events, 06(03n04), 2050003. https://doi.org/10.1142/s2345737620500037

Keuchenius, C. (2023). meting airco's en hittegolven.

Luber, G., & McGeehin, M. (2008). Climate Change and Extreme Heat Events. American Journal of Preventive Medicine, 35(5), 429–435. https://doi.org/10.1016/j.amepre.2008.08.021

Machard, A., Salvati, A., P. Tootkaboni, M., Gaur, A., Zou, J., Wang, L. L., Baba, F., Ge, H., Bre, F., Bozonnet, E., Corrado, V., Luo, X., Levinson, R., Lee, S. H., Hong, T., Salles Olinger, M., Machado, R. M. e. S., da Guarda, E. L. A., Veiga, R. K., ... Holzer, P. (2024). Typical and extreme weather datasets for studying the resilience of buildings to climate change and heatwaves. Scientific Data, 11(1). https://doi.org/10.1038/s41597-024-03319-8

NEN. (2021). HIGHLIGHTS NTA 8800. NEN.NL/EPG

Oropeza-Perez, I., & Østergaard, P. A. (2018). Active and passive cooling methods for dwellings: A review. In Renewable and Sustainable Energy Reviews (Vol. 82, pp. 531–544). Elsevier Ltd. https://doi.org/10.1016/j.rser.2017.09.059

Raftery, P. (2019). CBE Fan Tool. Center for the Built Environment.

Raftery, P., Cheung, T., Douglass-Jaimes, D., André, M., Li, J., Kent, M., Khoa Huynh, N., Sultan, Z., & Schiavon, S. (2023). Fans for cooling people guidebook. https://cbe-berkeley.gitbook.io/fans-guidebook/

RIVM. (2025, June 2). Evaluatie Nationaal Hitteplan: kans om te sterven door hitte sterk gedaald sinds 2010. https://www.rivm.nl/nieuws/evaluatie-nationaal-hitteplan-kans-om-te-sterven-door-hitte-sterk-gedaald-sinds-2010

Rovers, V. (2023). Koelbehoefte en gebruik van airco's en bodemwarmtepompen in woningen in 2022.

RVO. (2018). Temperatuuroverschrijding in nieuwe woningen in relatie tot voorgenomen BENG-eisen. Australasian Police Multicultural Advisory Bureau.

RVO. (2022). Voorbeeldwoningen 2022 bestaande bouw. In Rijksdienst voor Ondernemend Nederland.

Schellen, L. (2012). Beyond uniform thermal comfort : on the effects of non-uniformity and individual physiol ogy. https://doi.org/10.6100/IR737560

TNO. (2024, October 9). TNO voorziet forse groei energiegebruik van airco's. https://www.tno.nl/nl/newsroom/2024/10/groei-energiegebruik-airco/#:~:text=Eerder%20bleek%20al%20dat%20in,ook%20het%20energiegebruik%20voor%20koeling.

TNO, Rovers, V., Menkveld, M., Deltares, van de Brugge, R., Brolsma, R., & Pothof, I. (2022). Kennisagenda toekomstige koudevraag woningen.

van Marken Lichtenbelt, W., Pallubinsky, H., & Kramer, R. (2022). Creating health and resilience by a dynam ic indoor climate. https://doi.org/10.34641/clima.2022.232

World Meteorological Organization. (2023). Extreme Weather. https://wmo.int/topics/extreme-weather

Zuo, J., Pullen, S., Palmer, J., Bennetts, H., Chileshe, N., & Ma, T. (2015). Impacts of heat waves and corresponding measures: A review. Journal of Cleaner Production, 92, 1–12. https://doi.org/10.1016/j.jclepro.2014.12.078

9. APPENDICES

4.1 Interview Technical Specialist of ISSO

2. Publicaties en expertise:
Gespecialiseerd in binnenmilieu en thermisch comfort. Bijdragen aan o.a. ISSO 74, handboek bouwfysica, NTA 8800, en 'Integraal Ontwerpen voor Zomercomfort'.

Thermisch comfort en perceptie
3. Wat is thermisch comfort volgens ISSO?
ISSO 74 definieert comfort via de ATG-methode, maar in de praktijk is het sterk afhankelijk van beleving en controle over de omgeving.

4. Verschil woning vs. utiliteitsgebouw?
Ja, er is meer gedragsvrijheid thuis (bijv. kleding). Vermoeden bestaat dat de comfortgrens in woningen hoger mag liggen, maar dit is lastig te bewijzen.

4a. Verschillen grenswaarden?
Mogelijk wel, maar dit is nog niet officieel onderbouwd in ISSO 74.

4b. GTO in woning vs. kantoor?
GTO gebruikt vaste grenswaarden en is geschikt voor vergelijking, maar minder voor het meten van écht comfort.

Toereikendheid normen
5. Zijn huidige methoden toereikend?
GTO is eenvoudiger dan ATG, maar minder representatief. ATG is adaptiever maar complex. Discussie loopt nog over frequentie van overschrijding. Comfort is vaak situatieafhankelijk en gedrag speelt een grote rol.

5a. Eens met kritiek op ATG/GTO?
Ja, veel mensen verkiezen vaste waarden, maar dat levert niet altijd realistische inzichten op. Geen duidelijke richtlijn over acceptabele overschrijdingsduur.

Inzichten vanuit nieuwe ISSO-publicaties
6. Nieuwe inzichten ISSO 74 & Zomercomfort:

Erkenning van dynamisch comfort (temperatuur mag variëren).

Duidelijkere structuur en toelichting in nieuwe versies.

Behoefte aan betere methodes naast To-juli.

6a. Wie moet dit implementeren?
Ontwerpers, gemeenten, stedenbouwkundigen, installateurs. Paradigmaverschuiving nodig: eerst het gebouw ontwerpen op comfort, dan pas de installatie.

Prioriteit & afwegingen in maatregelen
7. Wat heeft prioriteit – koeling of verwarming?
Koeling. Begin met zonwering. Bekijk per situatie waar de grootste winst ligt.

8. Afwegingen bij maatregelen met neveneffecten:
Bomen geven schaduw, maar nemen wind weg en vergen water. Verdamping verlaagt temperatuur, maar verhoogt luchtvochtigheid. Glasbalans is belangrijk (HR++ vaak voldoende). Goed afwegen tussen daglicht en oververhitting.

Gedrag en gebruik in de praktijk
9. Behoeftes bewoners bij extreme hitte:
Comfort moet makkelijk en begrijpelijk zijn. Automatische systemen zijn handig, mits transparant. Brys-thermostaat als goed voorbeeld van gedragssturing.

10a. Praktische toepasbaarheid ISSO-methoden:
Niet altijd duidelijk voor bewoners. Meer laagdrempelige communicatie nodig (zoals flyers). Nationaal Hitteplan mist focus op woningmaatregelen.

Effectief gedrag en kennis
10b. Is er genoeg kennis bij bewoners?
Nee. Veel winst te behalen met eenvoudige, praktische voorlichting. Mensen weten vaak niet wanneer ze ramen juist wel of niet moeten openen.

11. Integratie 'Lagen van Koeling' in bestaande bouw:
Ja, maar per situatie bekijken. Omgevingseffecten (laag 1) zijn vaak gegeven; dan focus op gebouw (laag 3).

Verantwoordelijkheid & beleidsrol
12. Wie is verantwoordelijk voor koeltechnieken?
Iedereen speelt een rol, maar overheid moet kaders stellen. Marktpartijen worden gestuurd door economische belangen. Regulering creëert gelijke uitgangspositie.

Actieve technieken & kwetsbare groepen
13. Welke actieve techniek is het meest effectief?
Warmtepomp is vaak lucht-lucht (dus airco). Ventilatoren zijn laagdrempelig en persoonsgericht. Werken goed in praktijk ondanks beperkte temperatuurreductie.

14. Voor wie is airco onvermijdelijk?
In ziekenhuizen onmisbaar. In woningen soms nodig in slaapkamers, vooral bij kwetsbare groepen of hoge comfortverwachting (zoals expats).

14a. Kwetsbaarheid ouderen – gedrag of fysiek?
Beide. Fysiologische aanpassing neemt af met leeftijd. Comfortgrenzen mogelijk strenger nodig, maar regelgeving houdt hier nog geen rekening mee.

14b. Andere temperatuurgrenzen nodig voor ouderen?
Ja, maar lastig te implementeren. Complex bij gemengde eigendom (zoals seniorenwoningen). Noodzaak voor nadere differentiatie groeit.

15. Rol bewonersgedrag bij zomercomfort?
Gedrag is cruciaal. Zonder juiste toepassing werken maatregelen niet effectief.

16. Meer invloed op implementatie of juist gebruik?
Juist gebruik is belangrijker. Goede uitleg vooraf is essentieel om frustratie en inefficiëntie te voorkomen.

4.2 Architect

2. Thermisch comfort in Nederland
Prioriteit (nu en richting 2050): De focus verschuift van winter- naar zomercomfort. Oververhitting wordt een steeds groter probleem. Ontwerpmaatregelen zoals overstekken en strategische gevelopeningen worden belangrijker.

Wat is comfort? Comfort wordt vooral bepaald door oriëntatie, schaduw, leefgewoonten en beleving. Ontwerp begint vanuit leefwensen (zoals koel kunnen slapen) en natuurlijke elementen (zoals bomen en struiken).

Ontwerpen op extremen: Ja, gewerkt wordt met TO-juli en maandelijkse overschotberekeningen, vooral bij projecten met warmte-koudeopslag.

3. Regelgeving & normen
Toereikendheid regelgeving: Regelgeving stimuleert verduurzaming, maar is nog in ontwikkeling en soms verwarrend. Ambitieuze opdrachtgevers helpen duurzame keuzes realiseren, ondanks beperkingen van regelgeving.

Gebruik van bomen: Bomen bieden natuurlijke seizoensadaptatie (zonwering in zomer, lichttoetreding in winter), maar worden niet meegenomen in officiële berekeningen.

Ventilatoren: Worden praktisch toegepast (ook in kerken), vooral in hoge ruimtes of als natuurlijke trek via tegenoverliggende ramen mogelijk is. Niet meegenomen in regelgeving, maar effectief in de praktijk.

4. Koeltechnieken & toepassingen
Behoefte bewoners: Comfort = directe controle, werking, rust, verduistering, akoestiek, vooral in stedelijke context. Goede slaap is prioriteit.

Toegepaste technieken:

Pergola's als natuurlijke zonwering, met seizoensafhankelijke werking.

Groene daken zorgen voor verdamping en massa-koeling. Sedumdaken bieden verkoeling zonder veel gewicht, dikkere lagen vergroten biodiversiteit en buffering.

Ventilatoren zijn laagdrempelig en effectief op persoonsniveau.

Airconditioning: Beperkt en bewust toegepast, alleen in slaapkamers waar alternatief comfort niet haalbaar is. Geen voorkeur voor toepassing in leefruimtes.

Uitdagingen bij biobased bouwen:

Minder massa = minder warmteopslagcapaciteit.

Oplossingen: estrichvloer met zware korrels onder fermacell, herbruikbaar en circulair alternatief voor cementdekvloer.

5. Verantwoordelijkheid & beleid
Wie is verantwoordelijk?
Max ziet de overheid als hoofdverantwoordelijke voor implementatie van koeltechnieken via regelgeving. Alle andere ketenpartijen handelen binnen economische kaders of in opdracht. Alleen wettelijke normering zorgt voor brede toepassing van duurzame maatregelen.

6. Techniekkeuze & gedrag
Als je één techniek zou moeten kiezen: Niet expliciet benoemd, maar ventilatoren en passieve maatregelen (zoals overstekken en natuurlijke ventilatie) worden geprefereerd, airco alleen indien echt noodzakelijk.

Gedrag:

Gedrag speelt een cruciale rol in zomercomfort.

Effectieve voorlichting is essentieel om bewoners goed te laten omgaan met systemen zoals airco, vloerkoeling of natuurlijke ventilatie.

"Juist gebruik" is belangrijker dan "implementatie alleen".

7. Specifieke doelgroepen
Airco als enige optie:

In ziekenhuizen onmisbaar.

In woningen alleen als laatste stap, en alleen in slaapkamers.

Specifieke gebruikersgroepen zoals expats of mensen met hoge comfortverwachting kunnen airco wensen.

Ouderen en kwetsbaren: Niet besproken in detail in dit interview.

4.3 Physiologist

Thermofysiologie en Comfort
Introductie
De geïnterviewde is thermo-fysioloog en onderzoekt de invloed van omgevingstemperatuur op het menselijk lichaam, met name de stofwisseling. Hij werkt onder andere met modellen zoals ThermoSEM en het adaptieve comfortmodel.

Wat is thermisch comfort?
Thermisch comfort is subjectief, maar meetbaar via fysiologische modellen en vragenlijsten (zoals PMV of SET*). Factoren zoals acclimatisatie, dynamiek in temperatuur, en controle over de omgeving zijn belangrijk.

Binnen/buiten en ruimteverschillen?
Comfort wordt beïnvloed door locatie (slaapkamer vs. woonkamer) en omstandigheden. Het is gezond om soms buiten de thermoneutrale zone te zijn. Het lichaam past zich aan via doorbloeding, zweten of rillen.

Klimaatadaptatie en Normen
Wat moet prioriteit krijgen: koeling of verwarming?
Hoewel verwarming lange tijd dominant was, verschuift de aandacht naar koeling. Maar het standaard ontwerpen op extremen vindt hij niet wenselijk; dit leidt tot een smalle comfortzone.

Zijn huidige normen toereikend?
Nee. Alleen temperatuur is niet genoeg: ook luchtvochtigheid en luchtsnelheid zijn essentieel. De huidige normen (zoals PMV) zijn vaak te statisch en missen individuele variatie.

Koelstrategieën en Gezondheid
Wat is gezond of ongezond?
Acute blootstelling aan extreme kou of hitte is stressvol voor het lichaam. Gezond is juist regelmatige, milde blootstelling. Grote temperatuurverschillen (bijv. van 35°C buiten naar gekoeld binnen) zijn onwenselijk.

SET?*
Bekend, maar de geïnterviewde werkt liever met fysiologische parameters zoals huid- en kerntemperatuur in dynamische modellen.

Effect van gewenning en tijdsduur?
Acclimatisatie kan al na een week optreden. Mensen kunnen leren omgaan met hogere temperaturen door geleidelijke blootstelling.

Gedrag en Bewoners
Gedrag en beleving van comfort
Controle (zoals raam openen of thermostaat bedienen) verhoogt comfort. Maar schijncontrole werkt averechts. Gebruikers moeten echt effect voelen.

Invloed van gedrag
Gedrag speelt een grote rol. Mensen zouden beter moeten worden voorgelicht over hun installaties. Kennis is nog te beperkt.

Wie is verantwoordelijk?
Geen eenduidig antwoord, maar goede informatievoorziening aan bewoners is cruciaal.

Technieken en Strategieën
Aanbevolen technieken

Zonwering (passief) heeft de voorkeur.

Ventilatoren zijn effectief en energiezuinig (factor 10 lager verbruik dan airco).

Airco's maken mensen afhankelijker en gevoeliger voor hitte.

Alleen bij extreme hitte of voor kwetsbare groepen (zoals ouderen) is airco verantwoord.

Eén techniek als er geen beperkingen zijn?
Plafondventilator, vanwege de lage energievraag en bewezen comforteffect.

Voor welke doelgroepen is airco nodig?

Ziekenhuizen: absoluut noodzakelijk.

Ouderen of zieken: lagere comfortgrenzen en verminderde aanpassing.

In die gevallen kunnen airco's levensreddend zijn.

4.4 Association of Housing Corporations

Klimaatadaptatie
1. Belangrijkste vormen van klimaatverandering voor woningcorporaties:
Klimaatverandering leidt vooral tot hittestress, maar dit krijgt nog weinig prioriteit. De focus ligt op energie en wintercomfort, mede vanwege betaalbaarheid.
Vraag: Welke vormen van klimaatverandering zijn het belangrijkst voor woningcorporaties?

2. Huidige prioriteit: koeling of verwarming?
Verwarming krijgt nog steeds meer aandacht vanwege directe energiebesparing.
Vraag: Wat heeft nu de prioriteit?

3. Prioriteit in 2050: koeling of verwarming?
Koeling zal belangrijker worden, maar investeringen blijven lastig door kosten en politieke terughoudendheid.
Vraag: Wat heeft in 2050 de prioriteit?

4. Worden toekomstige scenario's meegenomen?
Nee, vanwege onzekerheden en kosten worden extremen niet standaard meegenomen.
Vraag: Worden toekomstige scenario's meegenomen in beslissingen?

5. Uitgangspunt bij verduurzaming:
Gemiddelde situatie, geen ontwerp op extremen.
Vraag: Ontwerp je op extremen of gemiddelden?

6. Wanneer is een woning "duurzaam"?
Bij isolatieverbetering en aansluiting op collectieve duurzame installaties, maar hittestress is geen harde eis.
Vraag: Wanneer zijn woningen duurzaam volgens corporaties?

Thermisch comfort
7. Wat is thermisch comfort in de praktijk?
Comfort is afhankelijk van seizoen en perceptie van de bewoner; afspraken gaan vooral over wintercomfort.
Vraag: Wanneer wordt een woning als thermisch comfortabel beschouwd?

8. Verschil zomer/wintercomfort:
Ja, hittestress krijgt nog weinig aandacht. Verduurzaming kan hitte juist verergeren bij slechte ventilatie.
Vraag: Is er een verschil tussen comfort in zomer en winter?

Normen en regelgeving
9. Zijn huidige normen toereikend?
Nee, TO-juli is beperkt toepasbaar. Nieuwe normen (NTA) moeten ook rekening houden met gezondheid en gedrag.
Vraag: In hoeverre zijn de huidige normen toereikend?

10. Gevolgen huurbevriezing voor verduurzaming:
Zonder huurverhoging is het behalen van de nationale prestatieafspraken financieel lastig.
Vraag: Heeft huurbevriezing invloed op verduurzaming?

Koeltechnieken in de praktijk
11. Wat willen bewoners?
Comfort zonder hitte, maar wat 'te warm' is verschilt sterk per persoon.
Vraag: Wat zijn de behoeften van bewoners bij hitte?

12. Kan corporatie rekening houden met gedrag?
Gedrag is moeilijk te beïnvloeden. Sensoren kunnen helpen, maar bewoners voelen zich snel betutteld.
Vraag: Kunnen corporaties rekening houden met bewonersgedrag?

13. Toegepaste koeltechnieken:
Zonwering, vaak geen vloerkoeling. Koeling via warmtenet beperkt.
Vraag: Welke koeltechnieken worden toegepast of aangeraden?

14. Wanneer komt een corporatie in actie?
Pas bij duidelijke signalen of veel meldingen.
Vraag: Wanneer ondernemen corporaties actie tegen oververhitting?

15. Nadelen koeltechnieken:
Zonwering draagt niet bij aan CO_2-reductie. Corporaties hebben netcongestieproblemen en installaties kosten veel geld.
Vraag: Welke nadelen zijn er bij koelmaatregelen?

16. Afwegingen bij negatieve neveneffecten:
Installaties kosten veel geld (aanschaf én onderhoud). Bij krap budget is comfort ondergeschikt aan energie.
Vraag: Wat speelt mee bij de keuze voor maatregelen ondanks nadelen?

17. Verantwoordelijkheid implementatie koeltechnieken:
Ligt bij meerdere partijen: overheid, corporatie, markt, bewoners. Corporaties moeten extra doen in versteende wijken.
Vraag: Wie is verantwoordelijk voor implementatie?

Gebruikersgedrag
18. Rol bewonersgedrag in zomercomfort:
Groot, maar moeilijk te beïnvloeden. Voorlichting en automatisering (sensoren) kunnen helpen.
Vraag: Welke rol speelt bewonersgedrag en hoe beïnvloed je dat?

19. Meer invloed op implementatie of gebruik?
Bewoners hebben meer invloed op gebruik dan op implementatie.
Vraag: Waar heeft de bewoner meer invloed op: keuze of gebruik?

Koeltechniek opties
20. Beste techniek bij geen limieten:
Geen concreet antwoord, maar airco als laatste redmiddel.
Vraag: Als alles mag, welke koelingstechniek kies je dan?

21. Actieve techniek als passieve niet genoeg is:
Koeling zou alleen voor kwetsbare doelgroepen moeten worden ingezet. TO-juli is lastig zonder koeling te halen.
Vraag: Wat werkt als passieve maatregelen niet genoeg zijn?

22. Doelgroep waar airco onvermijdelijk is:
Kwetsbare groepen. Er wordt beleid op gemaakt, maar behoefte aan richtlijnen blijft.
Vraag: Wanneer is airco onvermijdelijk?

4.5 Housing Corporation (2 people)

Thermisch Comfort

Wanneer is een woning van DUWO duurzaam?

Duurzaamheid is een dynamisch begrip. Ambities botsen soms met kosten en beperkte investeringsruimte. Duurzaam betekent: zoveel mogelijk studenten goed huisvesten, niet het ultieme passiefhuis realiseren.

Wat heeft nu de prioriteit in Nederland: koeling of verwarming?

Momenteel ligt de nadruk op wintercomfort en energiebesparing. Zomercomfort wordt nog beperkt meegenomen.

Wat heeft in 2050 de prioriteit: verkoelen of verwarmen?

De verwachting is dat koeling belangrijker wordt. Regelgeving verandert ook: het is niet meer genoeg om te kúnnen koelen, je moet ook bewijzen dat zomercomfort gewaarborgd is.

Wanneer is een gebouw volgens DUWO thermisch comfortabel?

Sinds kort is hittestress een duidelijke prioriteit. Er is een klachtenmonitoringssysteem in opbouw. In sommige complexe gevallen (zoals Leiden) werd uiteindelijk airco geïnstalleerd als noodmaatregel, maar passieve oplossingen hebben voorkeur. Betonkernactivering (zoals in Deventer) is een goed werkend voorbeeld.

Regelgeving en Normen

In hoeverre zijn huidige normen toereikend voor thermisch comfort?

Er zijn momenteel geen harde externe normen meer (huurcommissie neemt sinds 2024 geen zaken meer aan over bestaande bouw). TO-juli wordt als richtlijn gebruikt, maar geeft beperkt inzicht in werkelijke beleving. PMV zou accurater zijn. Men ervaart vaak al problemen bij TO-juli van 1–2, ondanks dat 4 als kritieke grens geldt.

Ventilatoren koelen wel, maar voldoen niet aan regelgeving. Gaat DUWO daar toch mee akkoord?

Geen expliciet antwoord, maar DUWO ziet ventilatie als belangrijke wens van bewoners. Door beperkingen bij studio's is natuurlijke dwarsventilatie vaak niet mogelijk, wat een structureel knelpunt vormt.

Koeltechnieken in de praktijk

Wat zijn de behoeftes van bewoners tijdens extreme hitte?

Veel bewoners vragen om betere ventilatiemogelijkheden, vooral in studio's. DUWO onderzoekt of die vragen voortkomen uit ervaren ongemak of geleerde verwachtingen. Er is dus ook aandacht voor perceptie.

Welke koeltechnieken past DUWO toe?

Bij nieuwbouw: vloerkoeling met change-over systeem. In bestaande bouw: Climarad wordt genoemd als effectieve oplossing (ventilatie + verwarming + nachtkoeling). Buitenzonwering is nog nauwelijks toegepast vanwege onderhoud, timing, gebruiksintensiteit en kosteneffectiviteit in studentenhuisvesting.

Verantwoordelijkheid en afwegingen

Wie is verantwoordelijk voor implementatie van koeltechnieken?

Bij structurele oververhitting ligt de verantwoordelijkheid bij de verhuurder. Bij persoonlijke voorkeuren (kortdurende hitte): bewoners kunnen ook eigen oplossingen zoeken, zoals ventilatoren. DUWO wijst op beperkte effectiviteit van maatregelen bij snel wisselende bewonerspopulaties (studenten).

Koeltechniek opties

Wat zou DUWO aanraden als er maar één techniek gekozen mocht worden, zonder beperkingen?

Voorkeur voor low-tech zoals grondbuizen. Adiabatische koeling en bypass-systemen worden in theorie genoemd, maar zijn in de praktijk vaak beperkt effectief door verkeerd ingestelde installaties.

Wat zijn energiezuinige actieve systemen als passieve maatregelen niet volstaan?

Climarad wordt als energiezuinig alternatief genoemd. Budget blijft echter altijd een beperkende factor. Niet alle oplossingen zijn toepasbaar in monumentale of bestaande gebouwen.

Is airco soms de enige optie? Voor welke doelgroep?
Voor studenten zelden noodzakelijk. Voor kwetsbare groepen (zoals ouderen) mogelijk wel. Airco als laatste redmiddel, afhankelijk van situatie.

Gebruikersgedrag
Welke rol speelt gedrag van bewoners bij het succes van zomercomfortstrategieën?
DUWO heeft nieuw proces: klacht beheerder flyer + meting mogelijke maatregel. Men wil systematischer te werk gaan m.b.v. een matrix (EDES) om geschikte maatregelen per situatie te bepalen.

Heeft de bewoner meer invloed op implementatie of juist gebruik van technieken?
DUWO ziet dat bewoners vooral invloed hebben op het juiste gebruik van installaties, maar bij studenten is kennisoverdracht lastig door jaarlijkse wisseling. Daarom focus op automatische, gedragsondersteunende systemen.

4.6 Technical Installations Advisor

Thermisch Comfort

3. Wanneer is een gebouw volgens jou thermisch comfortabel?

Ontwerpwaarden: 21 °C in de winter, 24,5 °C in de zomer.

Luchtvochtigheid wordt nauwelijks meegenomen vanwege energieverbruik.

Plafondsystemen of fan coils hebben de voorkeur boven vloerkoeling i.v.m. risico op condens.

4. Is er een onderscheid in thermisch comfort tussen woning en utiliteitsgebouw?

Ja, grote verschillen: labkoeling via luchtbehandeling (20x/h), kantoorventilatie veel lager (3x/h).

Koeltechniek in labs vraagt veel ruimte – vaak onderschat door architecten.

Bestaande gebouwen vragen om zorgvuldige integratie van toevoer/retourkanalen.

5. Zijn huidige normen toereikend voor thermisch comfort in woningen?

BBL is leidend bij bestaande bouw, maar adviseur zelf werkt vooral aan PvE's.

Engineers bewaken technische naleving; adviseur vertaalt gebruikersbehoefte naar systeemadvies.

6. Wat heeft nu prioriteit: koeling of verwarming?

Nog steeds verwarming, maar koeling wordt urgenter.

Innovaties zoals ijsbuffers en WKO worden belangrijker, maar zijn nu nog duur en moeilijk schaalbaar.

7. Wat heeft in 2050 de prioriteit: verkoeling of verwarming?

Verwachting: verschuiving richting koeling, zeker bij goed geïsoleerde woningen.

Collectieve oplossingen (zoals WKO op wijkniveau) bieden potentieel.

8. Wat zijn belangrijke uitdagingen bij verduurzamingsadvies?

Budget: investeringen komen van verhuurder, maar baten bij huurder.

Certificaten zoals BREEAM maken duurzame gebouwen wel aantrekkelijker voor huurders.

Spanningsveld tussen investeringsbereidheid en terugverdienmodel.

9. Welke afwegingen spelen mee bij maatregelen met bijeffecten?

Techniek vs. architectuur: bijv. gevels van glas verhogen koellast.

Maatregelen zoals overstekken, zonwering of zonoriëntatie moeten vroeg in het ontwerp meegenomen worden.

PCM's zijn potentieel nuttig, maar nog onbetrouwbaar door afhankelijkheid van temperatuurfluctuaties.

Koeltechnieken

10. Welke praktische koeltechnieken gebruik je graag?

WKO is favoriet: duurzaam en efficiënt, mits goed gebalanceerd.

Bij onbalans (zoals bij Politieacademie) zijn extra systemen nodig.

Zonwering en oriëntatie zijn cruciaal om warmtelast te beperken.

11. Wordt passieve koeling toegepast?

Nauwelijks bij grote gebouwen; energie-eisen vaak te hoog.

Wel bij woningen: natuurlijke ventilatie, isolatie en zonwering.

Ventilatoren verhogen comfort zonder echte koeling – zelden toegepast in NL.

12. Wie is verantwoordelijk voor implementatie van koeltechnieken?

Gebruiker ervaart het dagelijks, maar opdrachtgever beslist uiteindelijk.

Adviseur neemt koeling altijd mee in advies, maar uitvoering hangt af van klant.

Gebruikersgedrag
13. Welke rol speelt gedrag in zomercomfort?

Groot: gebruikers zetten ramen open tijdens actieve koeling   systeem werkt minder goed.

Soms worden "nep"-thermostaten geplaatst voor gevoel van controle.

Ramen soms permanent gesloten om gedrag te sturen.

14. Heeft bewoner meer invloed op implementatie of gebruik van koeling?

Meestal meer invloed op gebruik dan op implementatie.

Bewustwording en ontwerpbeslissingen rond gedrag spelen een rol.

Koeling in specifieke situaties
15. Is actieve koeling soms de enige oplossing?

Ja, bij specifieke functies zoals laboratoria of zwaarbelaste gebouwen.

Passieve maatregelen vaak onvoldoende bij hoge interne warmtelast.

16. Welke koelingstechniek zou je kiezen zonder beperkingen?

WKO: efficiënt, duurzaam, en geschikt voor seizoensopslag van energie.

Bodemgesteldheid in Nederland is gunstig voor deze techniek.

4.7 Building Physics Consultant

Thermisch Comfort

1. Wanneer is een gebouw volgens jouw thermisch comfortabel?
Comfort is meer dan luchttemperatuur — ook stralingstemperatuur telt mee. Een woning met enige temperatuurschommeling voelt vaak prettiger dan een volledig constant binnenklimaat. Ontwerpen zoals overstekken helpen om deze balans op natuurlijke wijze te bereiken.

2. Is er een onderscheid tussen thermisch comfort in woningen versus utiliteitsgebouwen?
Ja. In woningen is hitte extra relevant vanwege slaapcomfort en gezondheid, in utiliteitsgebouwen vooral vanwege productiviteit. Bij woningcorporaties groeit de vraag naar oplossingen vóór de oplevering, vooral sinds invoering van TO-juli.

3. Zijn huidige normen voldoende voor thermisch comfort?
TO-juli is complex en wordt vaak slecht begrepen, ook door professionals. Soms leidt het tot onlogische eisen (bv. zonwerend glas op noordgevels). Zonwering en zonwerend glas hebben ook nadelen (donker, onderhoud). In bestaande bouw wordt TO-juli informeel steeds vaker toegepast, zeker bij renovatieprojecten.

Klimaatadaptatie

4. Wat heeft nu de prioriteit: koeling of verwarming?
Nog steeds verwarming, vanwege de hogere kosten. Toch groeit de aandacht voor koeling, vooral door de opkomst van warmtepompen.

5. Wat heeft in 2050 de prioriteit?
Vermoedelijk een sterke focus op koeling, maar met behoud van seizoensverschillen. WKO's blijven geschikt mits de energiebalans in stand blijft. Mogelijk moet men in de toekomst 'verplicht' verwarmen om die balans te behouden.

6. Wat zijn de grootste uitdagingen bij verduurzamingsadvies?
Complexiteit van hitteproblematiek maakt communicatie lastig. Visualisaties van temperatuurontwikkeling zijn effectiever dan technische indicatoren zoals GTO. Er heerst nog weinig urgentie zolang hitte als incidenteel probleem wordt gezien.

7. Welke afwegingen spelen bij maatregelen met negatieve neveneffecten?
Zonwerend glas kan in winter comfort verminderen. Soms kiest men alsnog voor zulke maatregelen om aan regelgeving te voldoen, eventueel na simulatieberekening om vrijstelling te krijgen.

Praktische koeltechnieken

8. Wat zijn praktische koeloplossingen?
Overstekken en zonwering op strategische oriëntaties zijn effectief. Zonwering liever verticaal aan noord/oostzijde bij veel glas. Ook zoneverwarming (alleen verwarmen waar nodig) is energiezuinig. Dubbel glas vaak beter dan triple glas vanwege lichtdoorlaat en kosten. Spuien is cruciaal bij goed geïsoleerde woningen zonder actieve koeling.

8a. Hoe zit het met luchtkwaliteit bij spuien?
CO_2 stijgt snel binnen; even 15 min ventileren is vaak voldoende. Spuien is effectief bij begin/eind van de dag.

Verantwoordelijkheid & gedrag

9. Wie is verantwoordelijk voor koeltechnieken?
Opdrachtgevers (bv. woningcorporaties) beslissen, maar installateurs en adviseurs beïnvloeden sterk via prestatieberekening. Corporaties volgen meestal dat advies, tenzij ze actief doorvragen.

10. Wat is de rol van bewonersgedrag en hoe kan dat beïnvloed worden?

Gedrag is belangrijk, zeker bij passieve systemen. Mensen vergeten vaak tijdig te spuien of zetten ventilatiesystemen niet goed aan. Goed ontwerp (bv. automatische systemen, bypass) kan gedragsafhankelijkheid beperken. Bewoners weten vaak niet goed hoe systemen werken.

11. Heeft de bewoner meer invloed op implementatie of gebruik?
Gebruik. Zelfs goed ontworpen systemen worden slecht gebruikt als kennis of discipline ontbreekt. Daarom moet comfort zo passief mogelijk zijn.

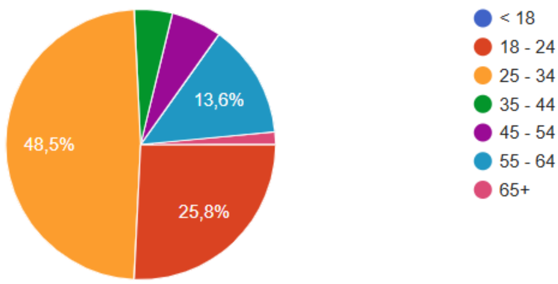
Specifieke situaties
12. In welke gevallen is actieve koeling de enige oplossing?
Bij kwetsbare groepen of extreme hitte. Hoewel niet wenselijk, is actieve koeling tegenwoordig eenvoudig toe te voegen aan warmtepompen. Bij gebruik van vloerkoeling is aandacht voor luchtvochtigheid belangrijk (risico op condens).

13. Wat is je voorkeurskoelsysteem bij geen beperkingen en voldoende budget?
Bodemwarmtepomp (diepe boring, 150–200 m). Stil, efficiënt, geen visuele hinder, en goede balans tussen verwarming en passieve koeling. Bodemtemperatuur blijft stabiel — ook in 2050.

4.8 Questionnaire Results - Background Information

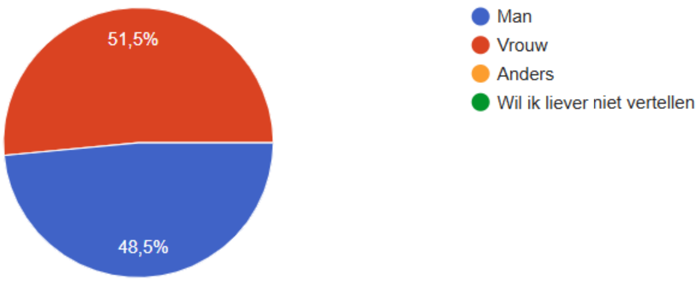
Wat is uw leeftijd?

66 antwoorden



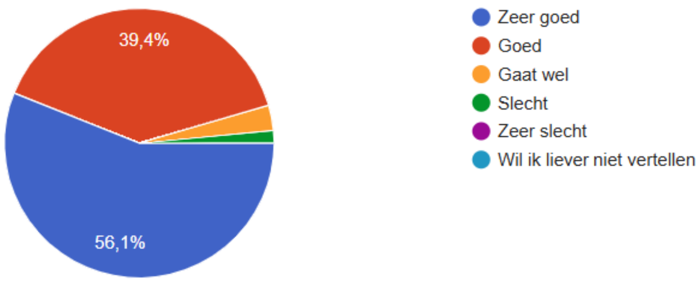
Hoe identificeert u zichzelf?

66 antwoorden



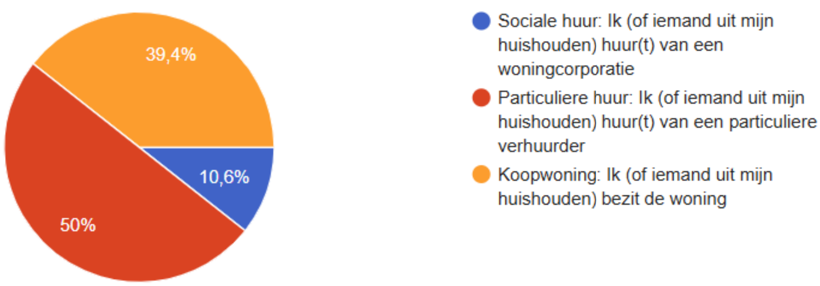
Hoe is over het algemeen uw gezondheid?

66 antwoorden



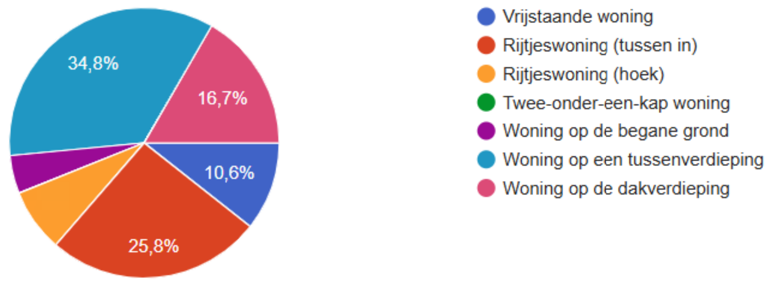
Wat is uw woonsituatie?

66 antwoorden



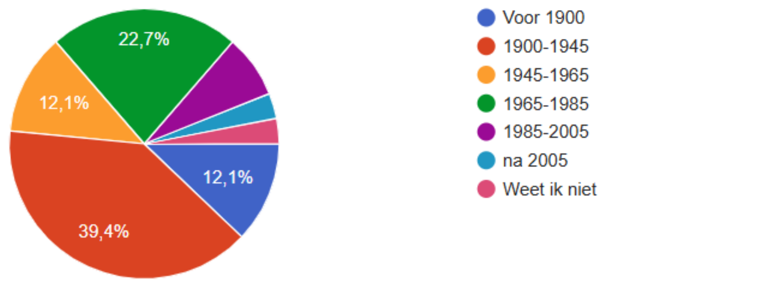
Wat voor soort woning bewoont u?

66 antwoorden



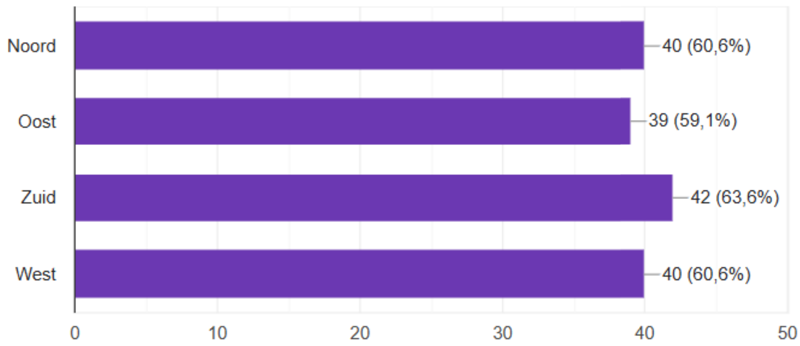
Wanneer is uw woning gebouwd denkt u?

66 antwoorden



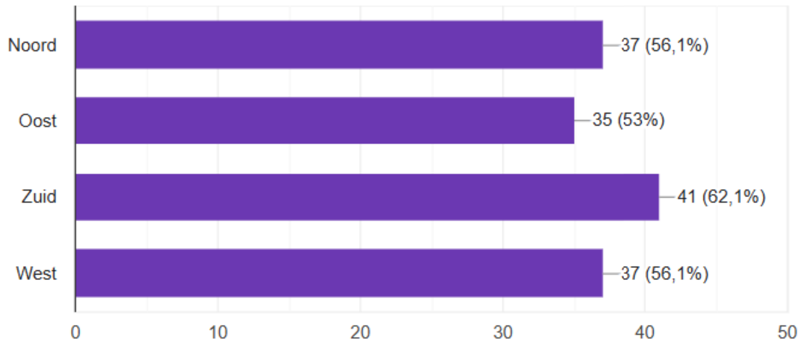
Welke zijde(s) van uw huis bevat(ten) ramen?

66 antwoorden



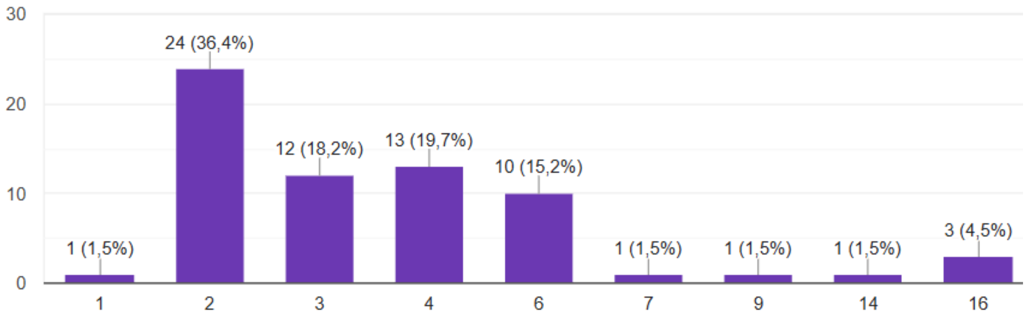
Welke zijde(s) van uw huis bevat(ten) ramen die open kunnen naar de buitenkant?

66 antwoorden



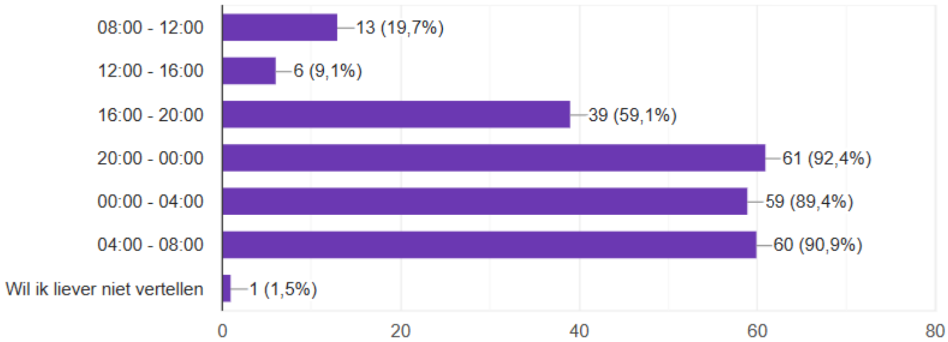
Hoeveel personen, inclusief uzelf, wonen in uw woning?

66 antwoorden



Tussen welke uren bent u gewoonlijk thuis op een doorsnee dag?

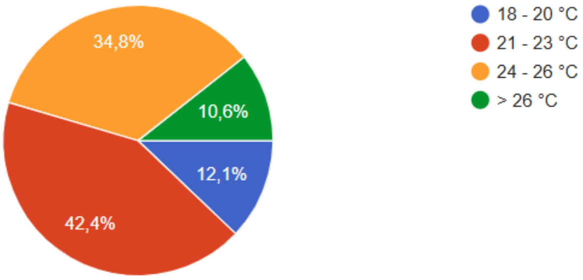
66 antwoorden



4.9 Questionnaire Results - Perception of Thermal Comfort

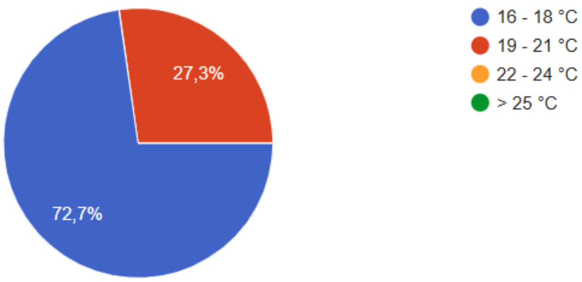
Wat is voor u de maximale bovengrens van temperatuur binnen uw woning?

66 antwoorden



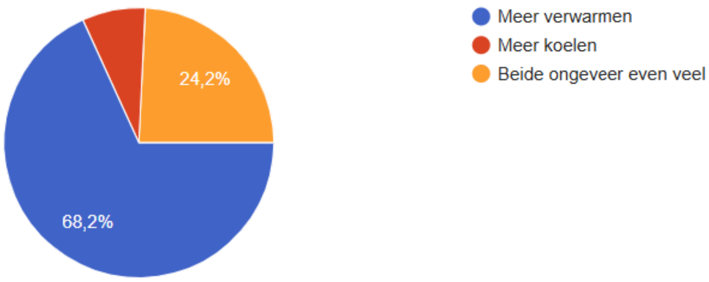
Wat is voor u de maximale ondergrens van temperatuur binnen uw woning?

66 antwoorden



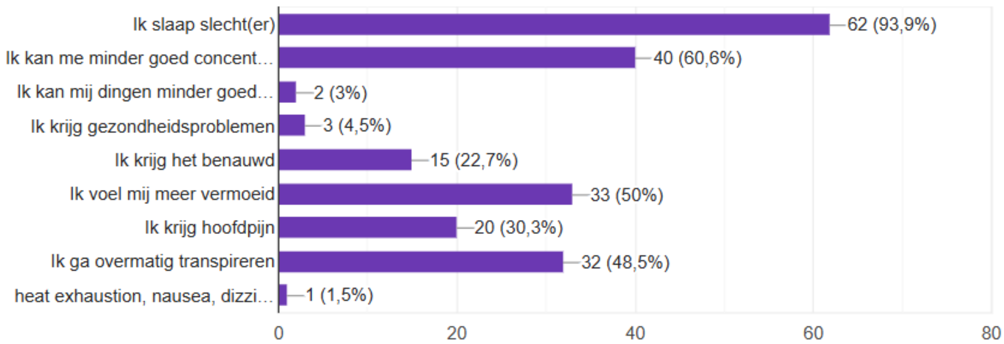
Moet u gedurende het jaar meer verwarmen of koelen om aan bovenstaande grenswaarde te voldoen?

66 antwoorden



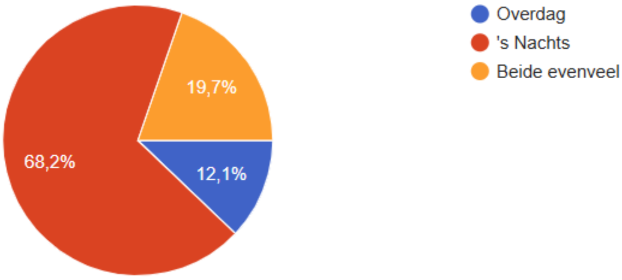
Als het niet lukt om uw woning voldoende te koelen, wat ervaart u dan wanneer het binnen **te warm** is?

66 antwoorden

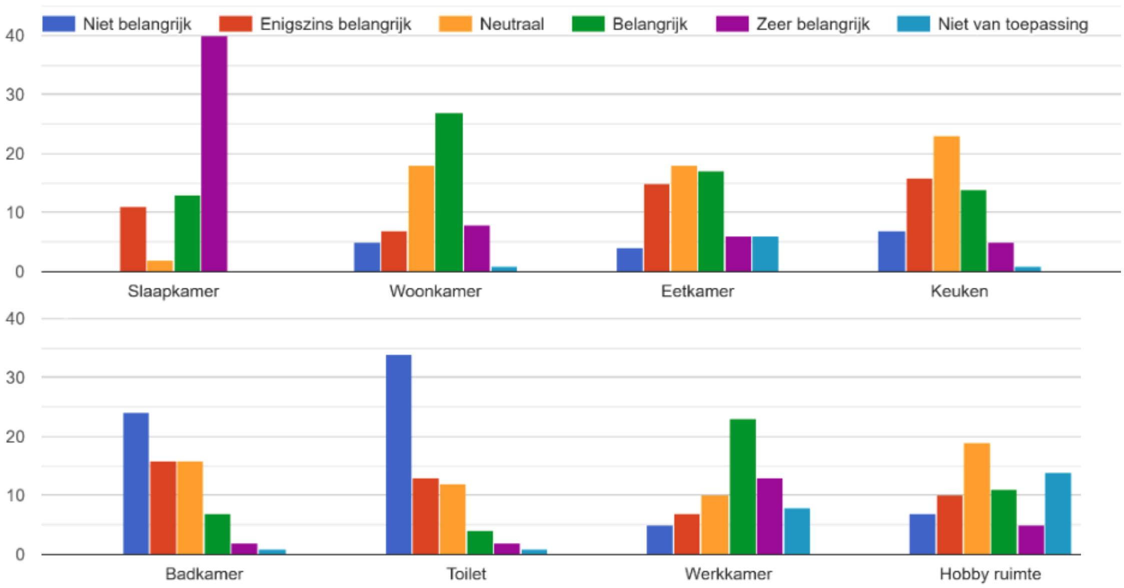


Op welk moment van de dag vindt u een comfortabel (koel) binnenklimaat het belangrijkst op een warme dag?

66 antwoorden

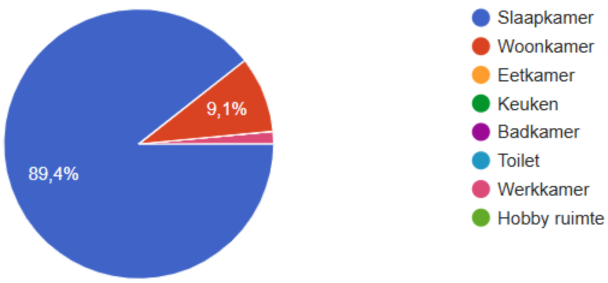


Kunt u per ruimte aangeven hoe belangrijk u voldoende koeling vindt?



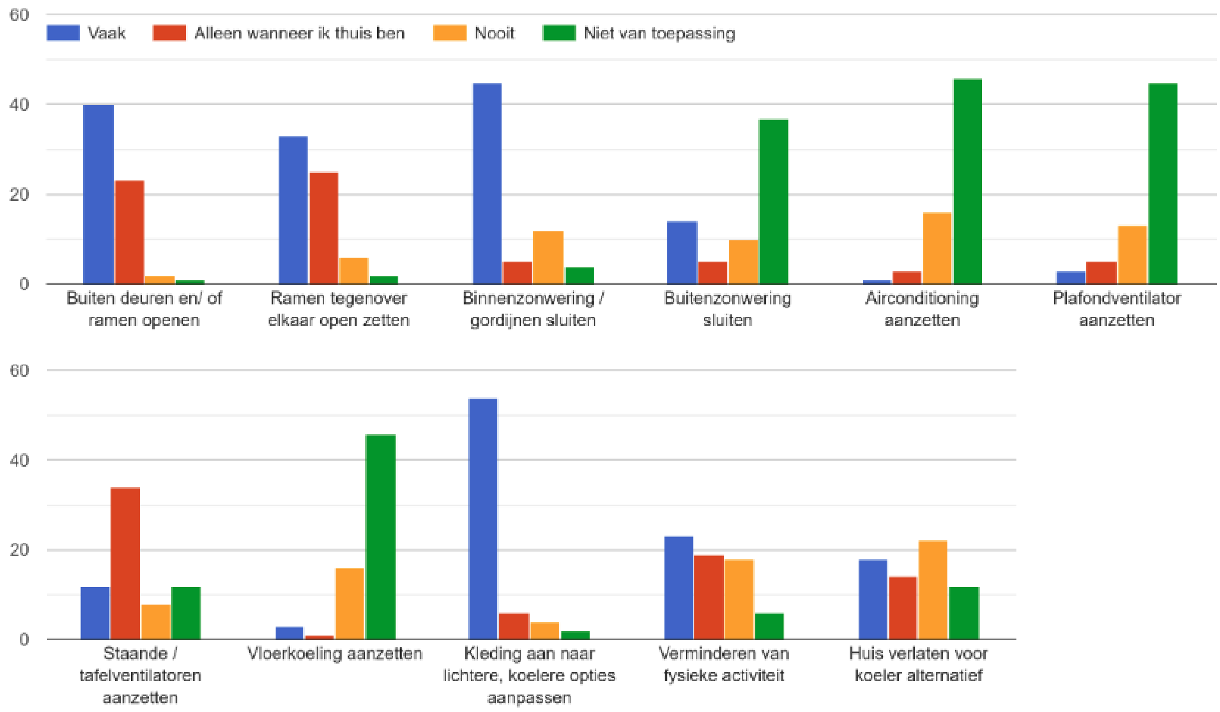
Als u een budget had om één ruimte in uw woning tijdens de zomer constant comfortabel koel te houden, welke ruimte zou u dan kiezen?

66 antwoorden

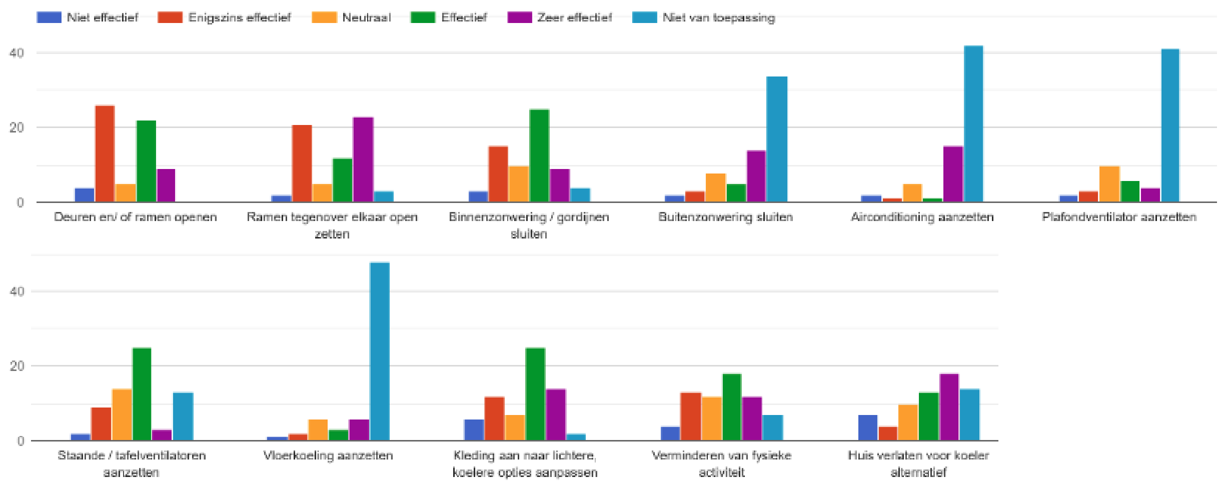


4.10 Questionnaire Results - Cooling Strategies and Effectiveness of Cooling

Welke strategieën gebruikt u momenteel om uw woning of uzelf te koelen op een **(te) warme** dag?

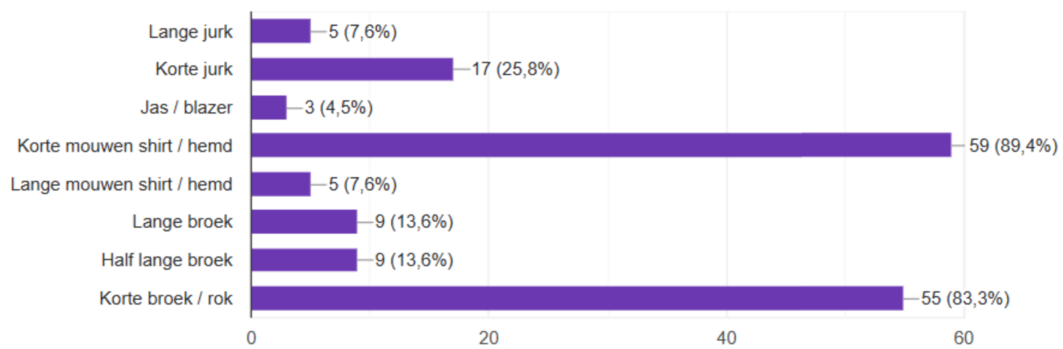


Hoe effectief vindt u die koelstrategieën in het bereiken en behouden van een aangename, koelere binnentemperatuur?



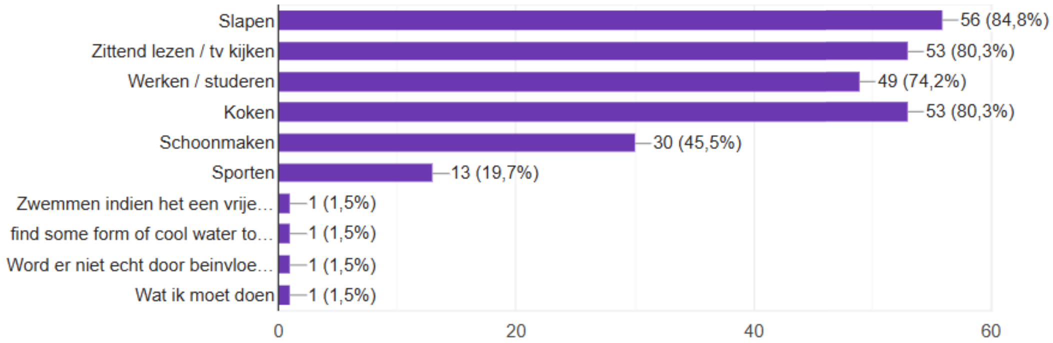
Welke kleding draagt u thuis op een **(te) warme** dag?

66 antwoorden



Welke activiteiten onderneemt u thuis, zelfs op een **te warme** dag?

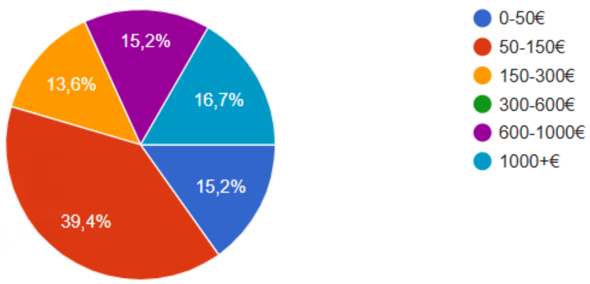
66 antwoorden



Wat zou u, samen met uw huishouden, ongeveer willen uitgeven om uw woning tijdens warme zomerdagen aangenaam koel te houden?

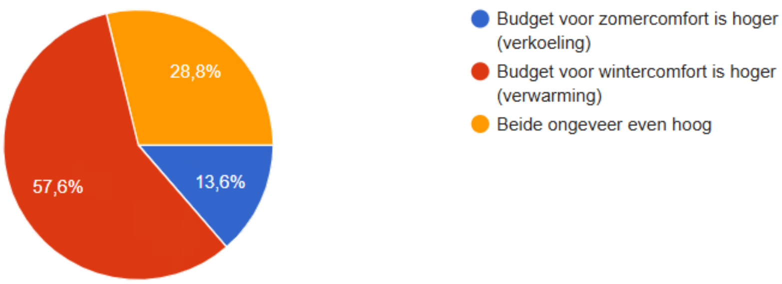
Diagram kopiëren

66 antwoorden



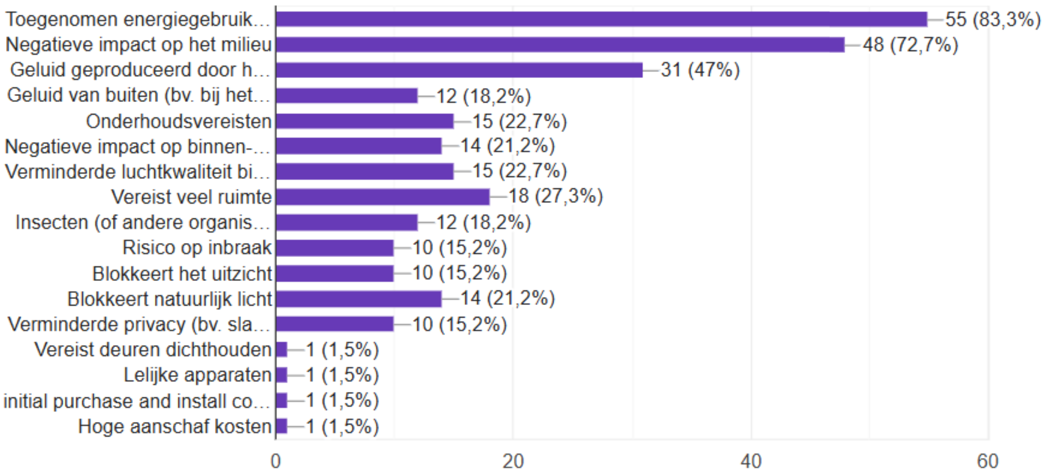
Hoe verhoudt het hierboven genoemde budget zich tot het bedrag dat u bereid bent uit te geven aan verwarming tijdens de winter?

66 antwoorden



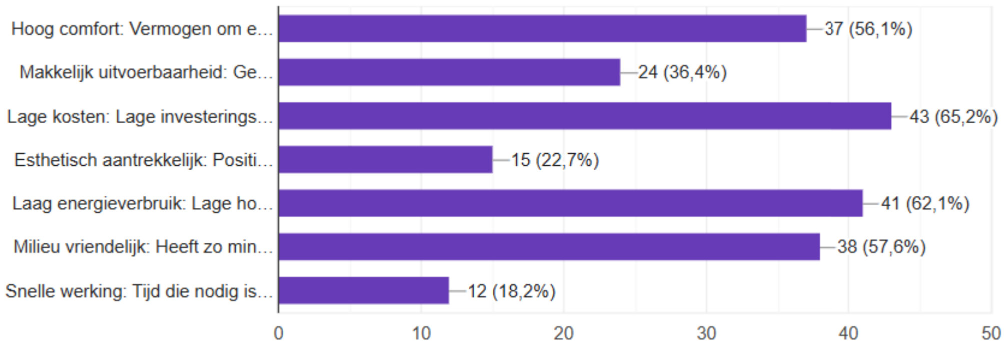
Wat beschouwt u als een negatief bijeffect van een koelstrategie en daarmee een reden om deze **niet** aan te schaffen of te gebruiken?

66 antwoorden



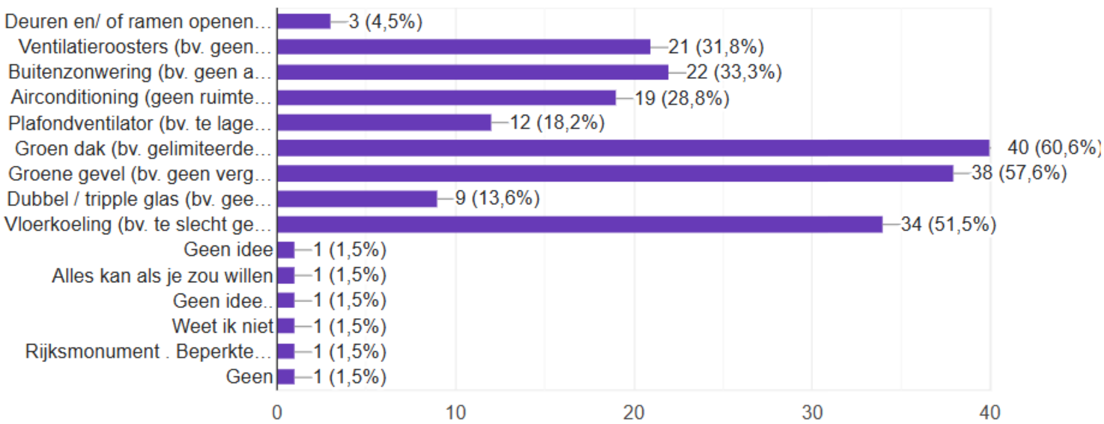
Stel, u kunt investeren in een manier om uw woning te koelen. Welke drie aspecten vindt u dan het belangrijkst dat deze oplossing bevat?

66 antwoorden



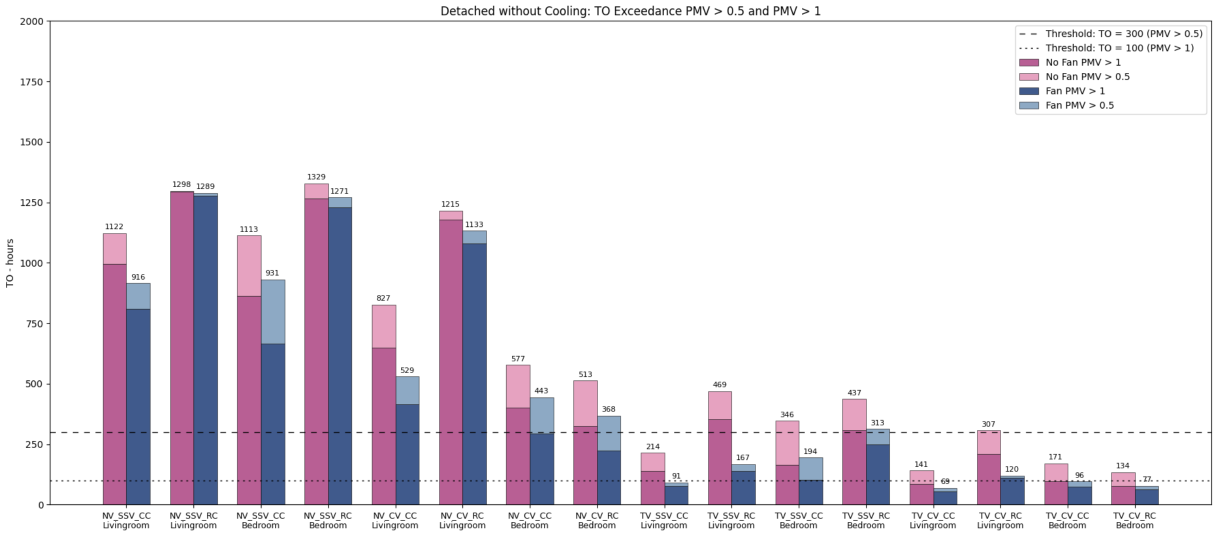
Welke koelingsstrategie zou, volgens u, **niet** in uw woning toegepast kunnen worden?

66 antwoorden

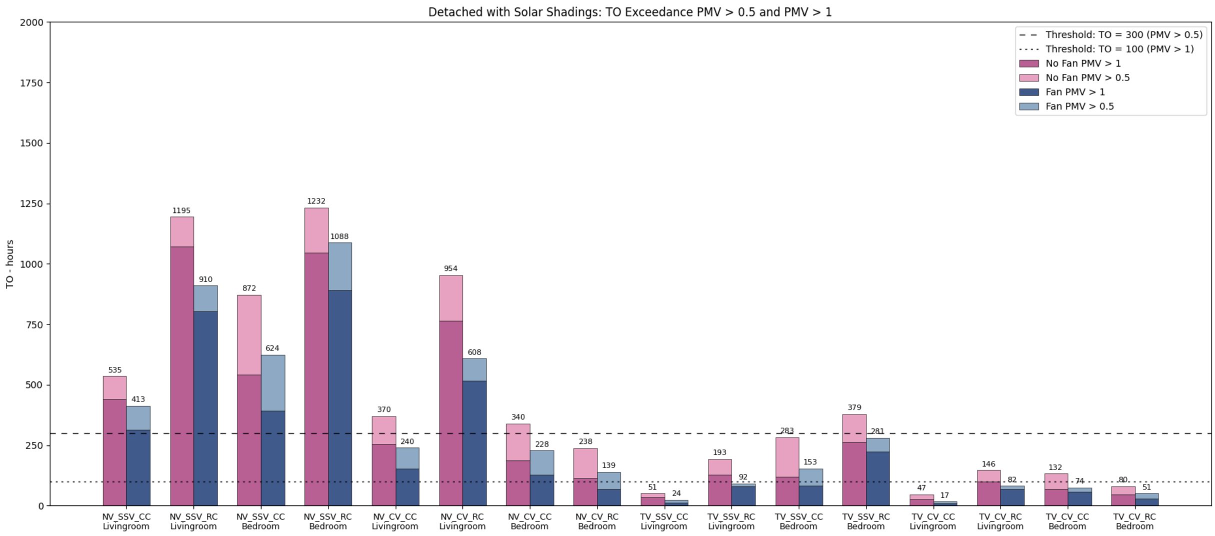


5.1 TO-hours for Detached Residence

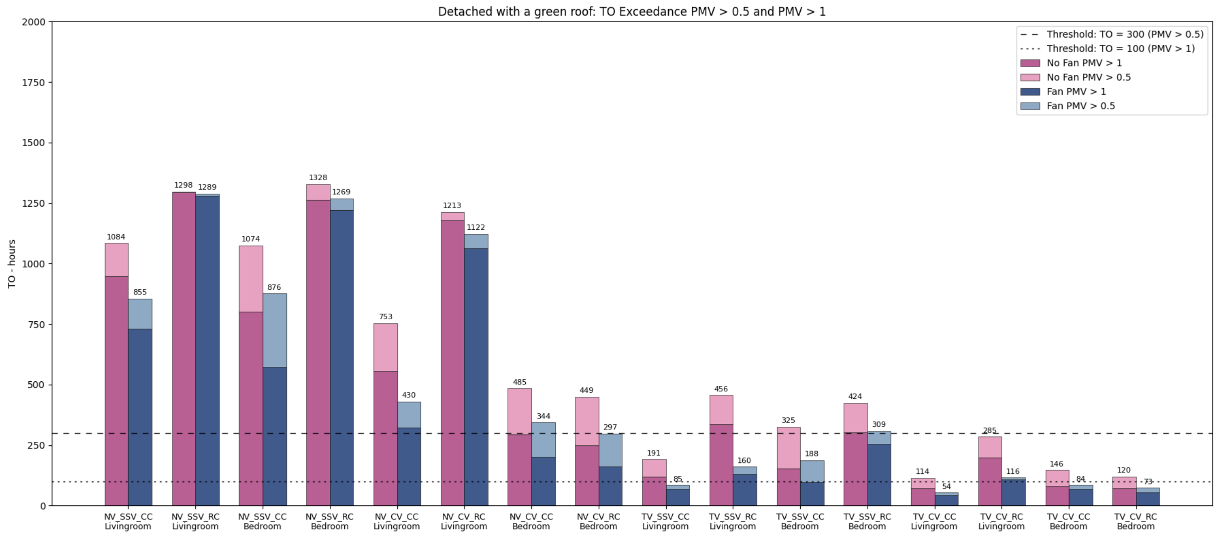
5.1.1



5.1.2

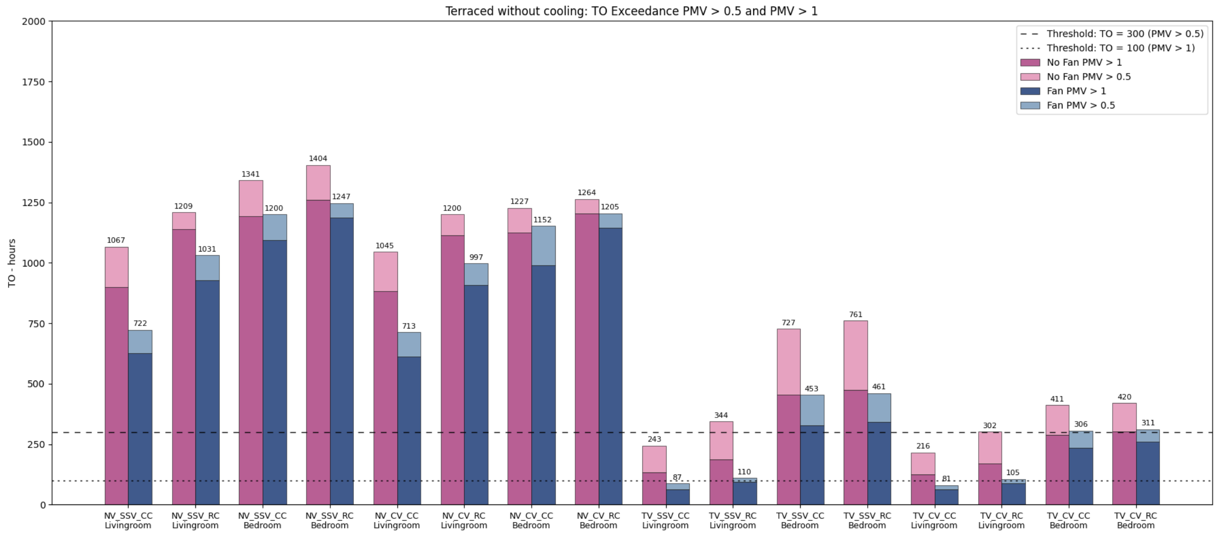


5.1.3

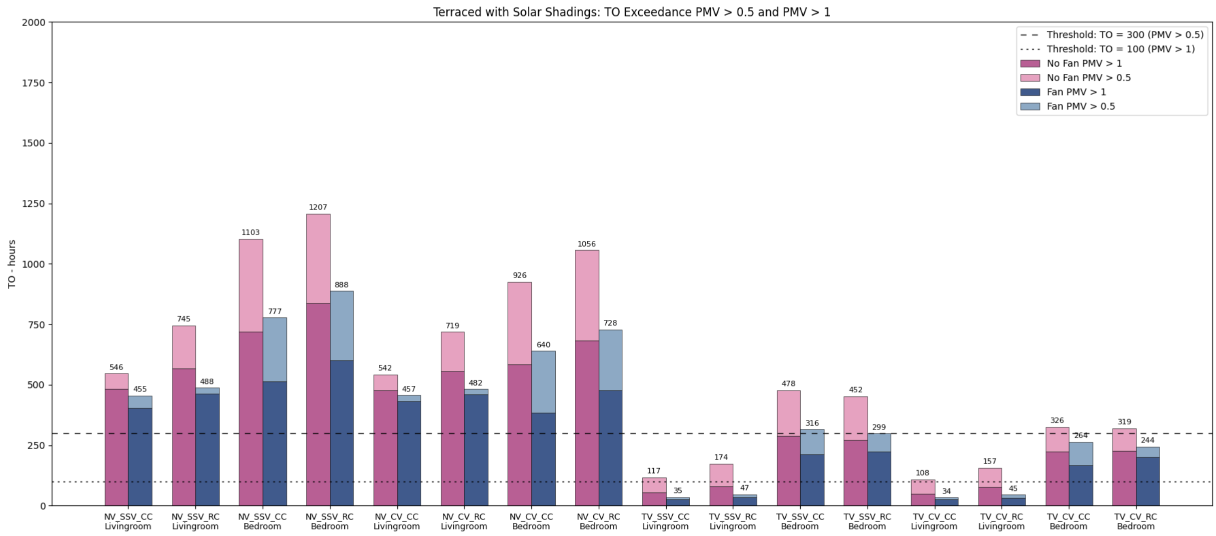


5.2 TO-hours for Terraced Residence

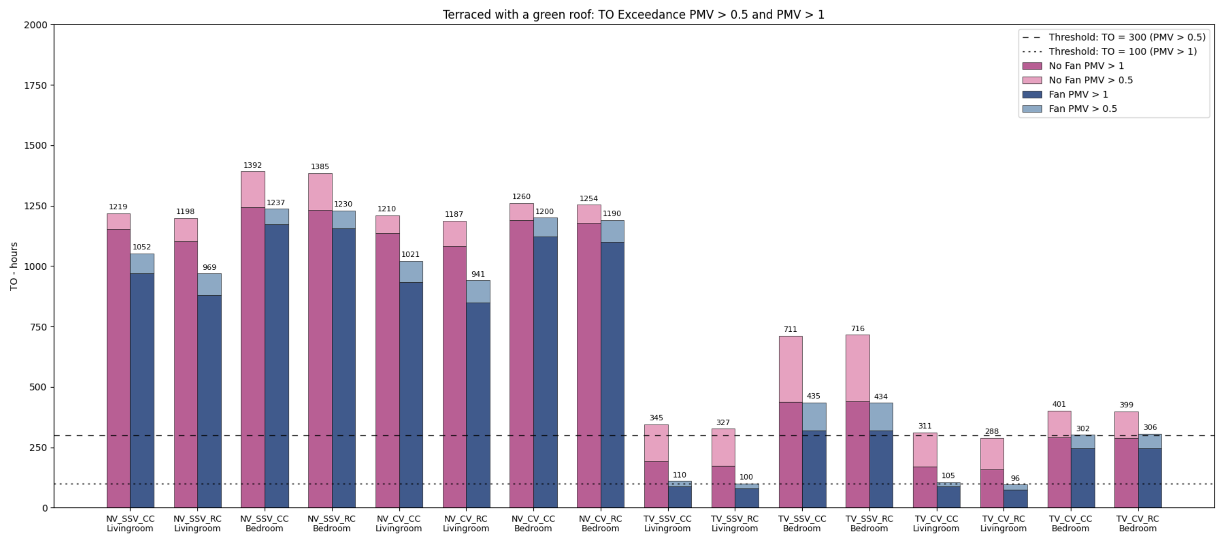
5.2.1



5.2.2

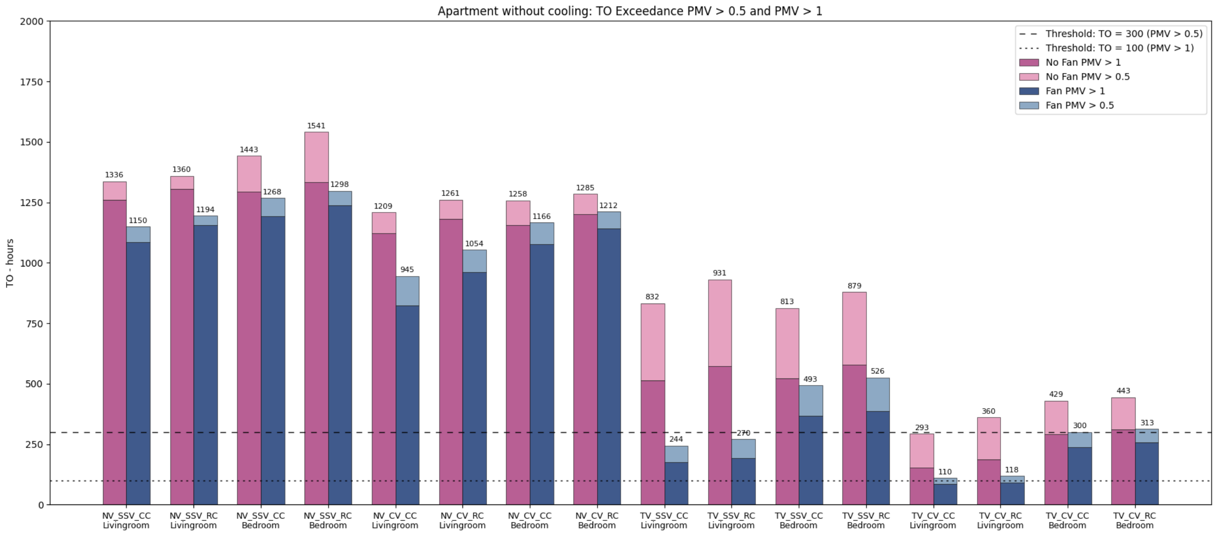


5.2.3

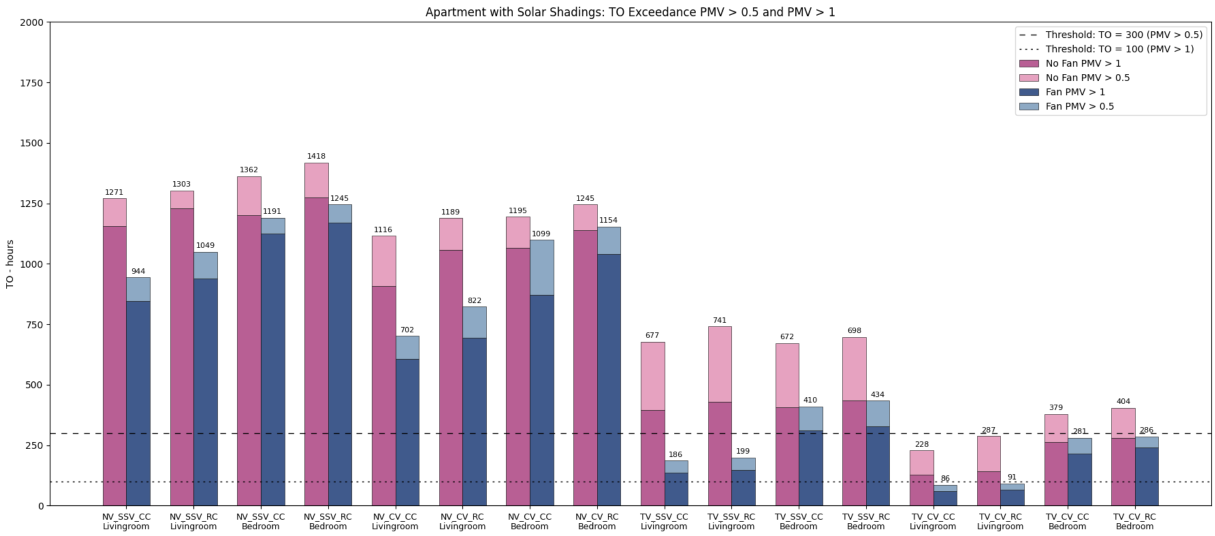


5.3 TO-hours for Apartment

5.3.1

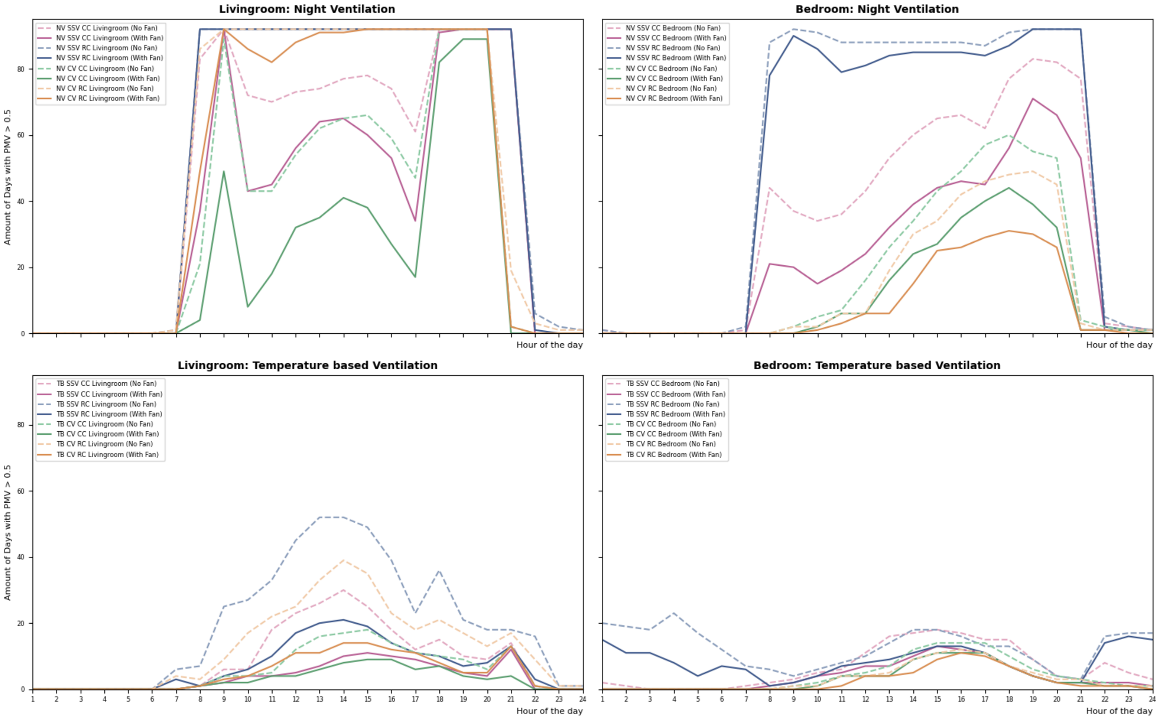


5.3.2

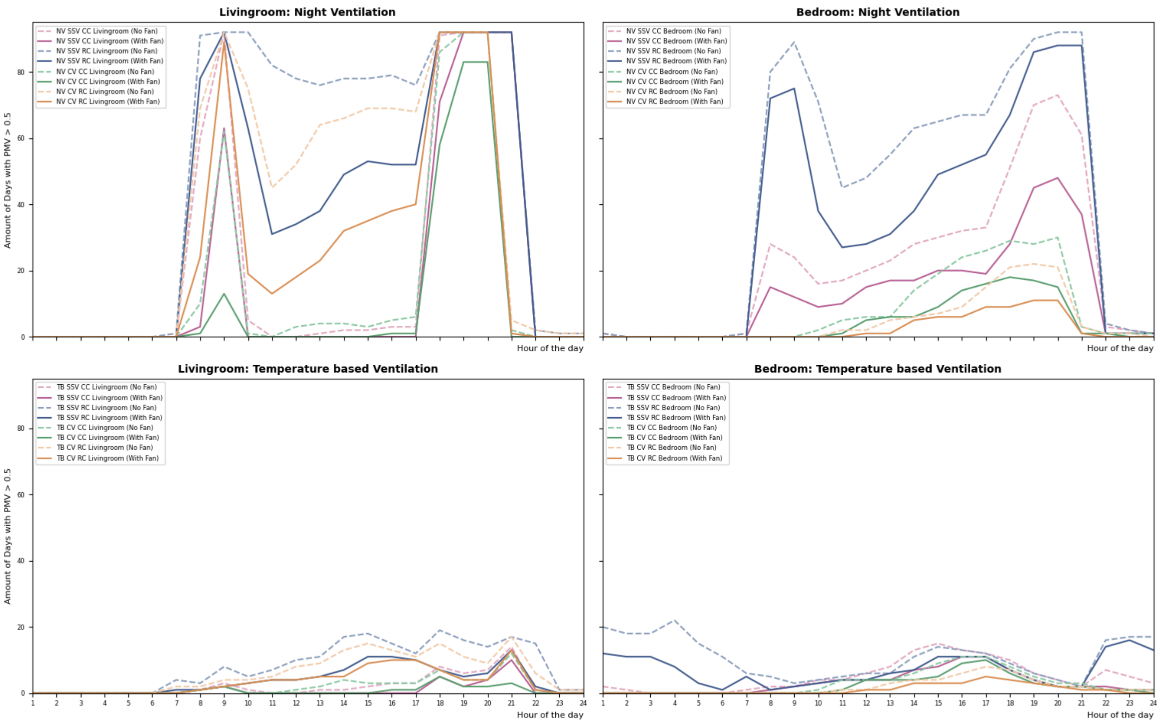


5.4 Amount of days with TO Exceedance (PMV>0.5) per hour of the day - Detached

5.4.1 Baseline

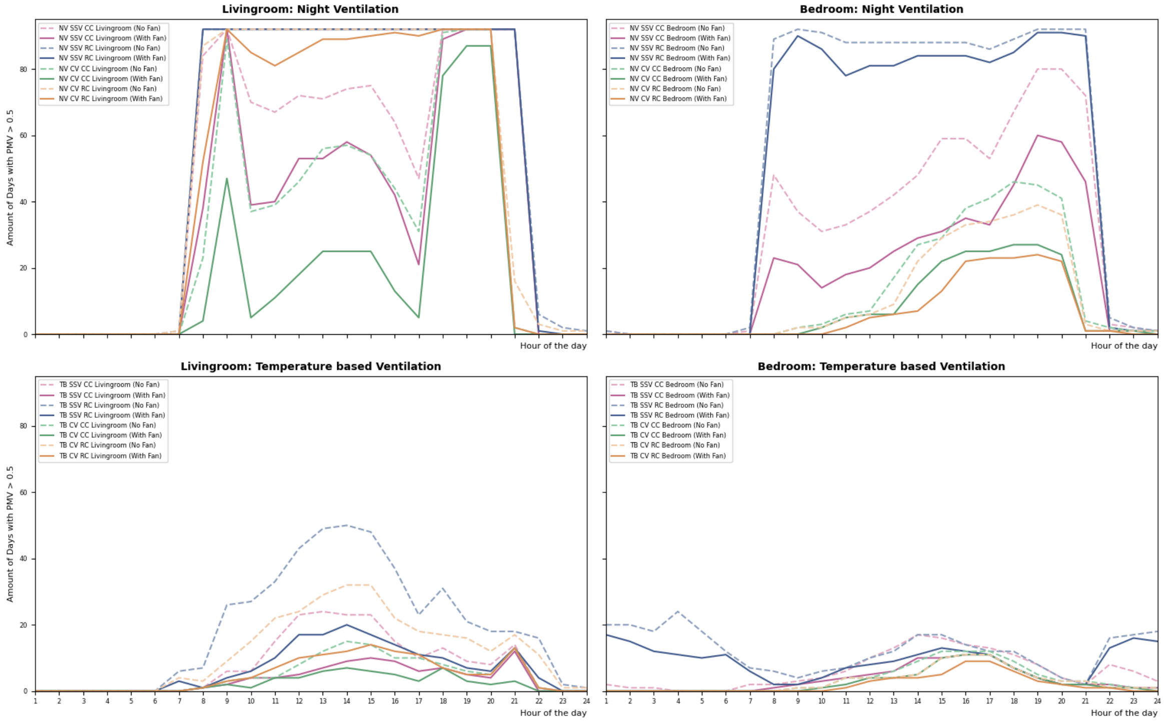


5.4.2 Solar Shading



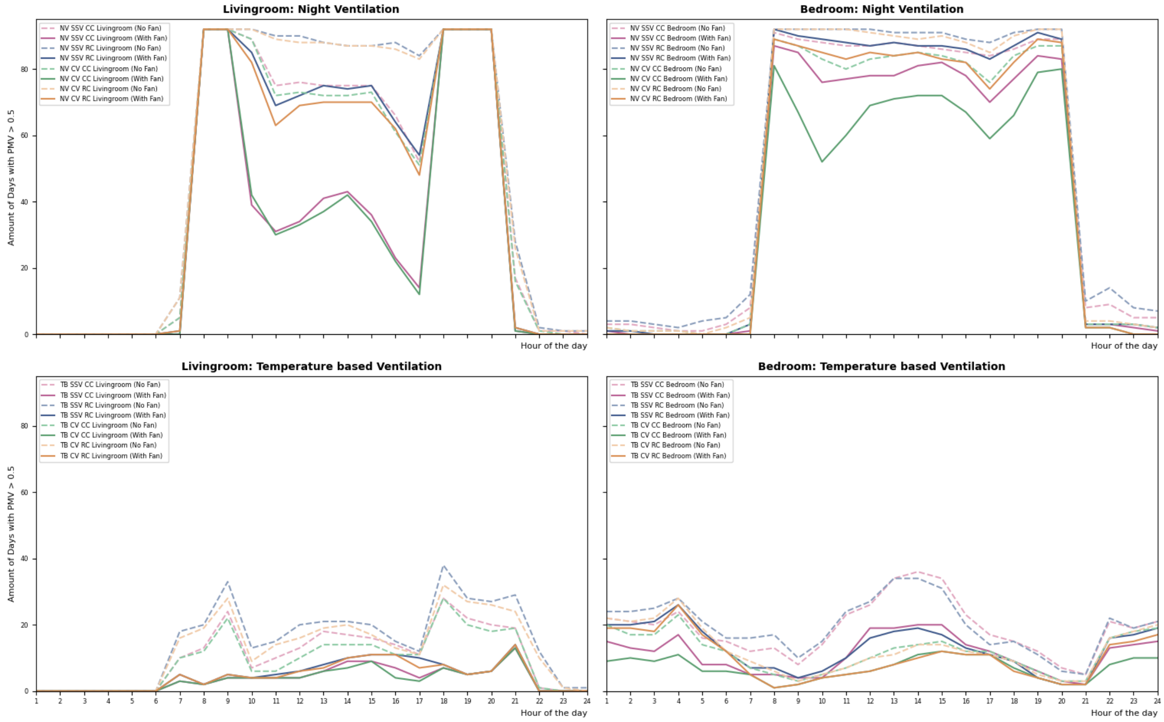
5.4 Amount of days with TO Exceedance (PMV>0.5) per hour of the day - Detached

5.4.3 Green Roof

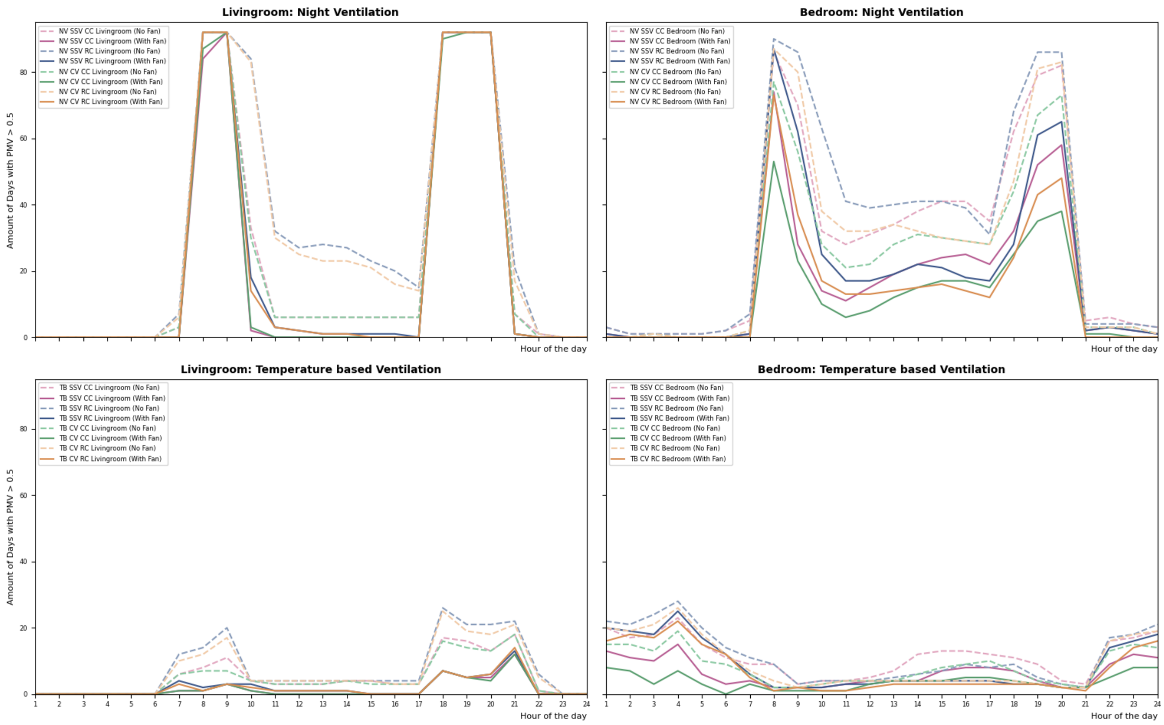


5.5 Amount of days with TO Exceedance (PMV>0.5) per hour of the day - Terraced

5.5.1 Baseline

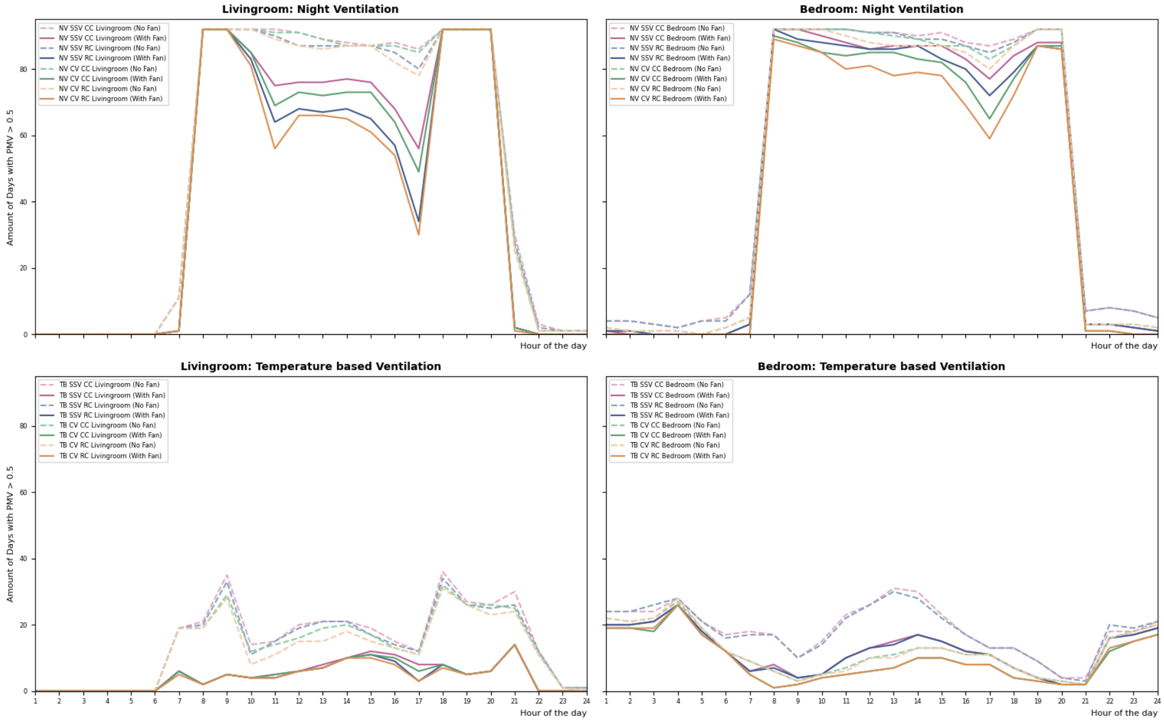


5.5.2 Solar Shading



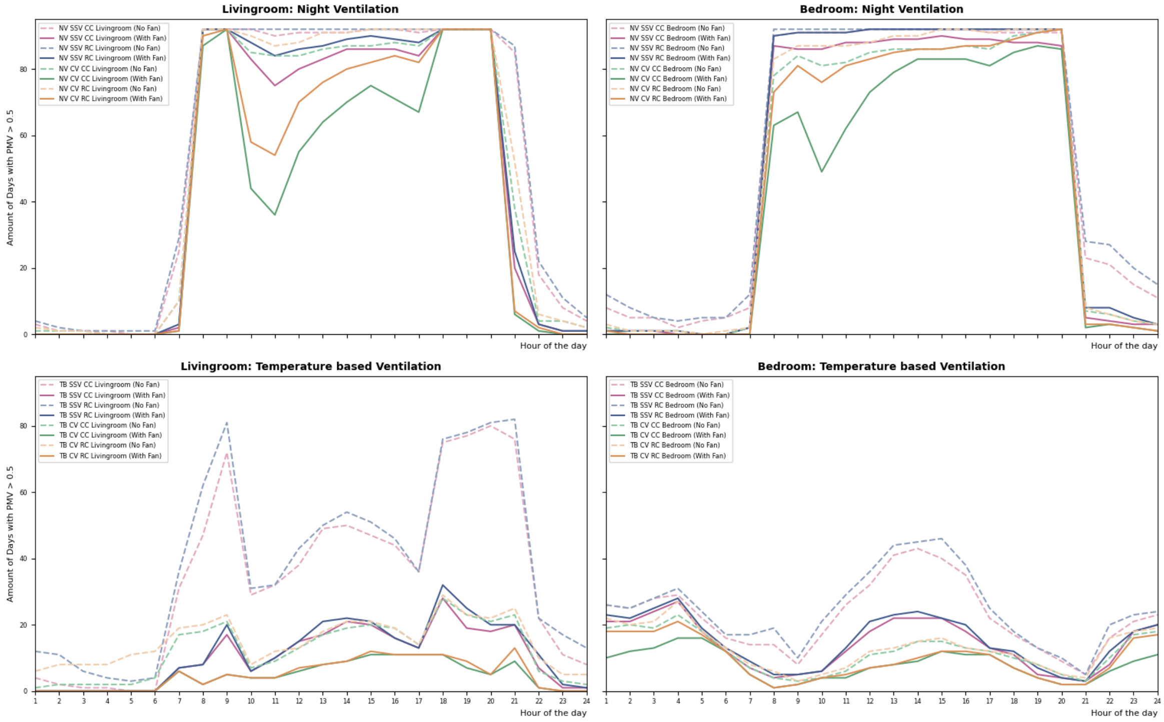
5.5 Amount of days with TO Exceedance (PMV>0.5) per hour of the day - Terraced

5.5.3 Green Roof

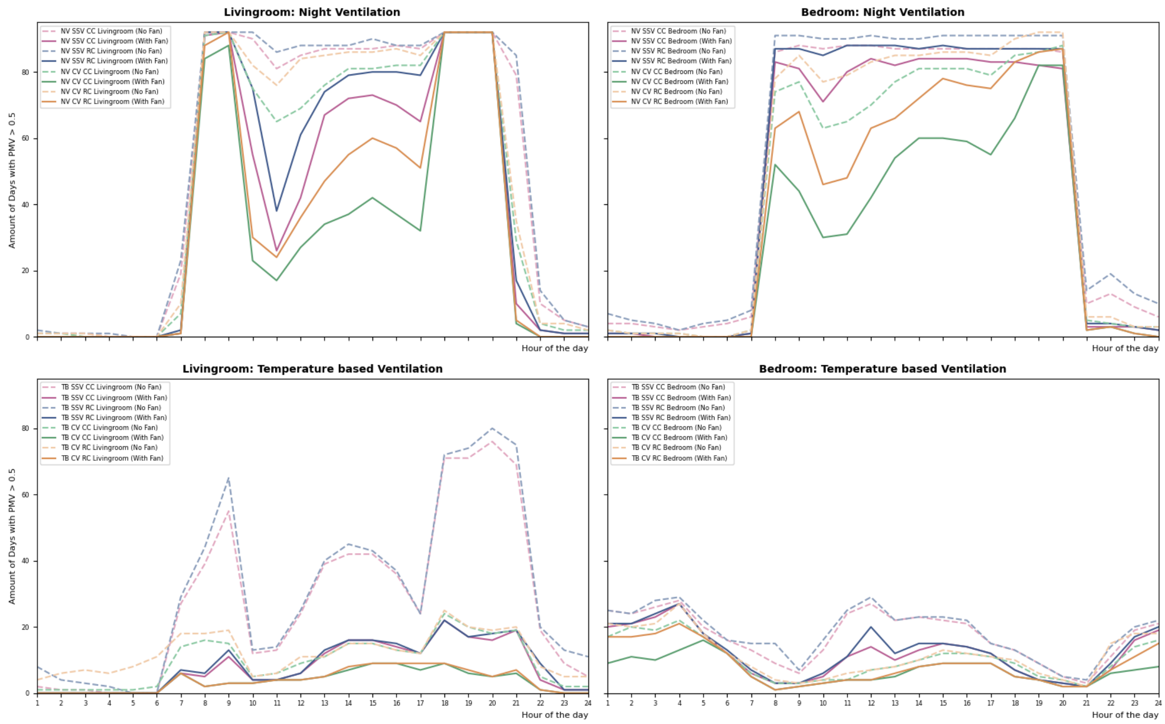


5.6 Amount of days with TO Exceedance (PMV>0.5) per hour of the day - Apartment

5.6.1 Baseline

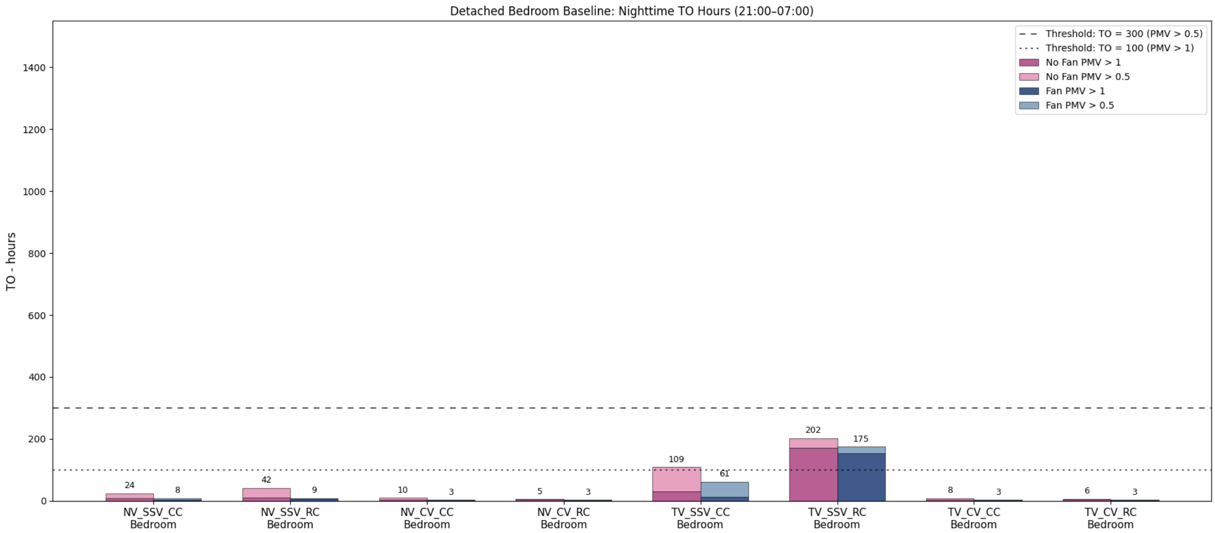


5.6.2 Solar Shading

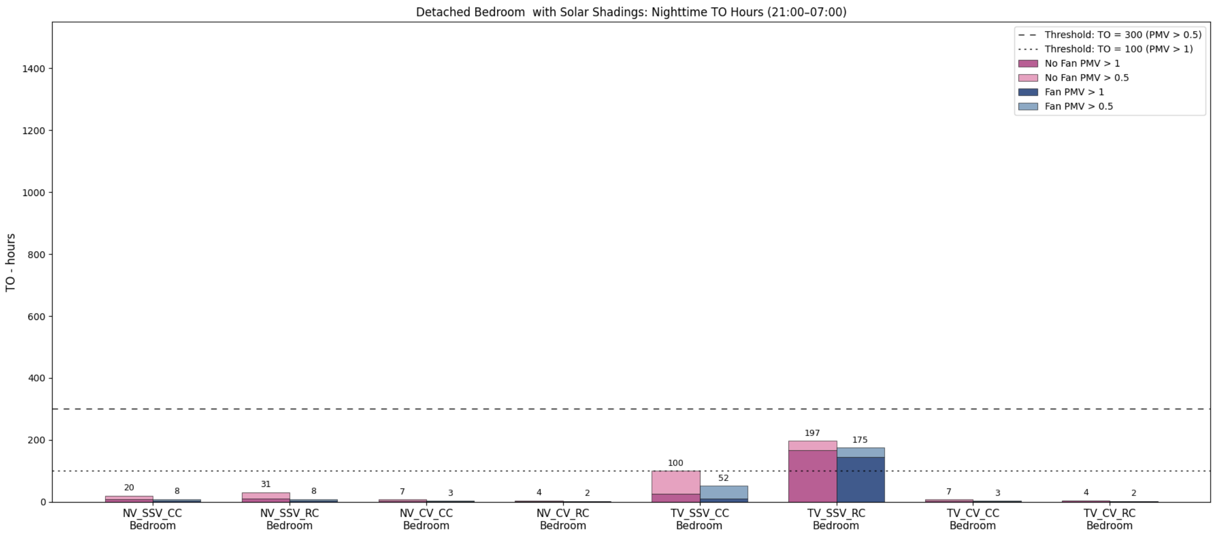


5.7 TO-hours (PMV>0.5 & PMV>1) during 21:00 - 07:00 in the Bedroom - Detached

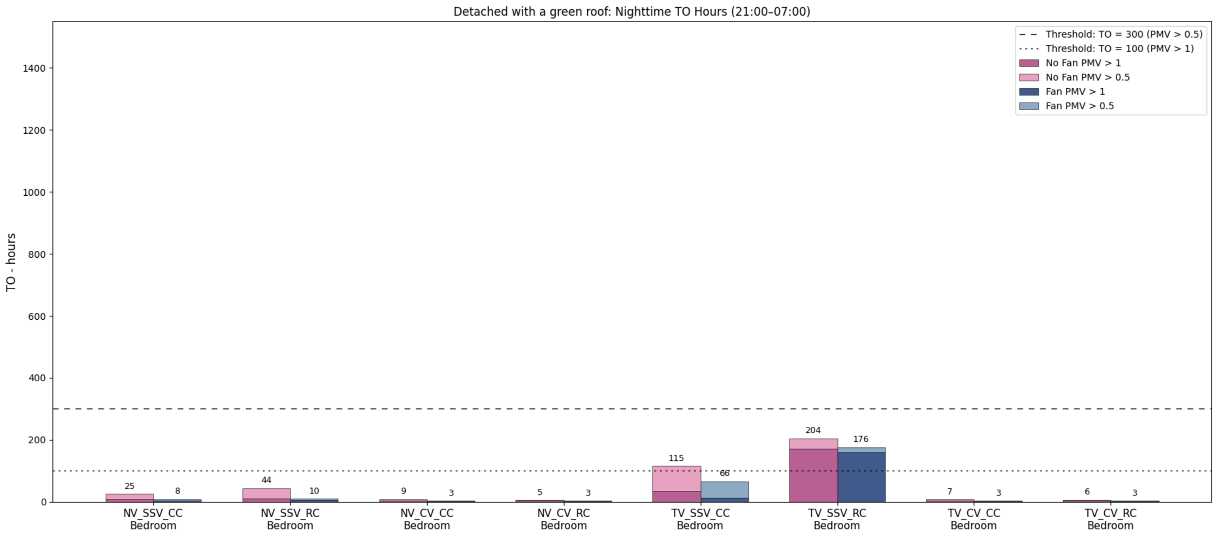
5.7.1



5.7.2

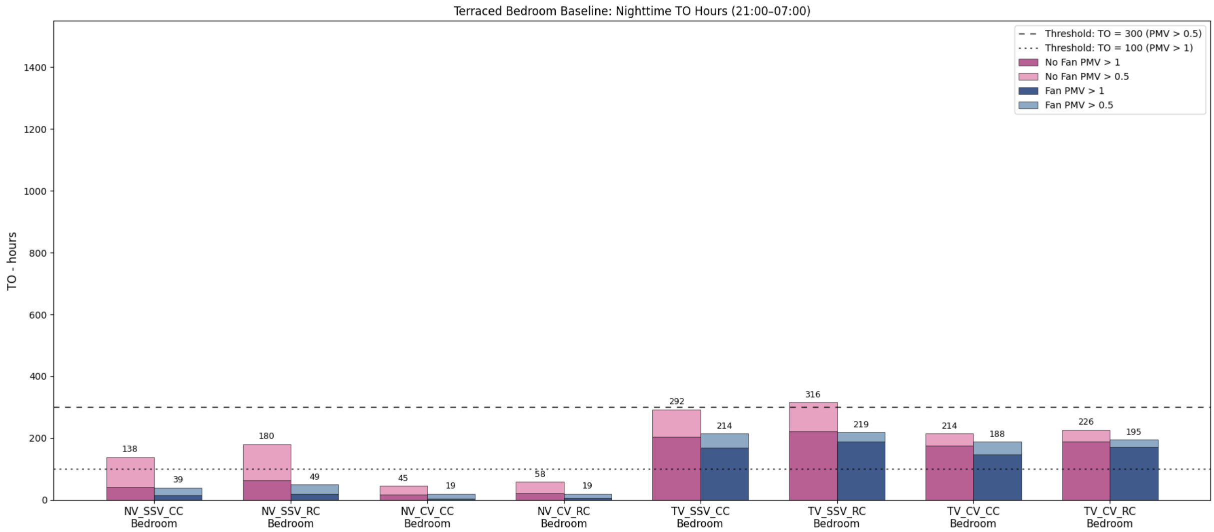


5.7.3

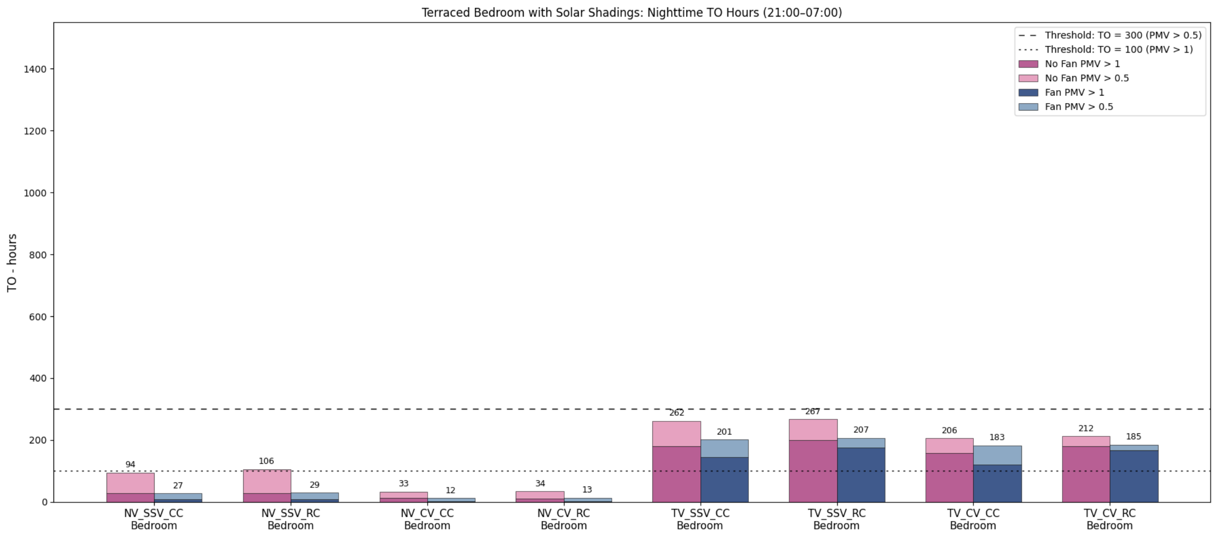


5.8 TO-hours (PMV>0.5 & PMV>1) during 21:00 - 07:00 in the Bedroom - Terraced

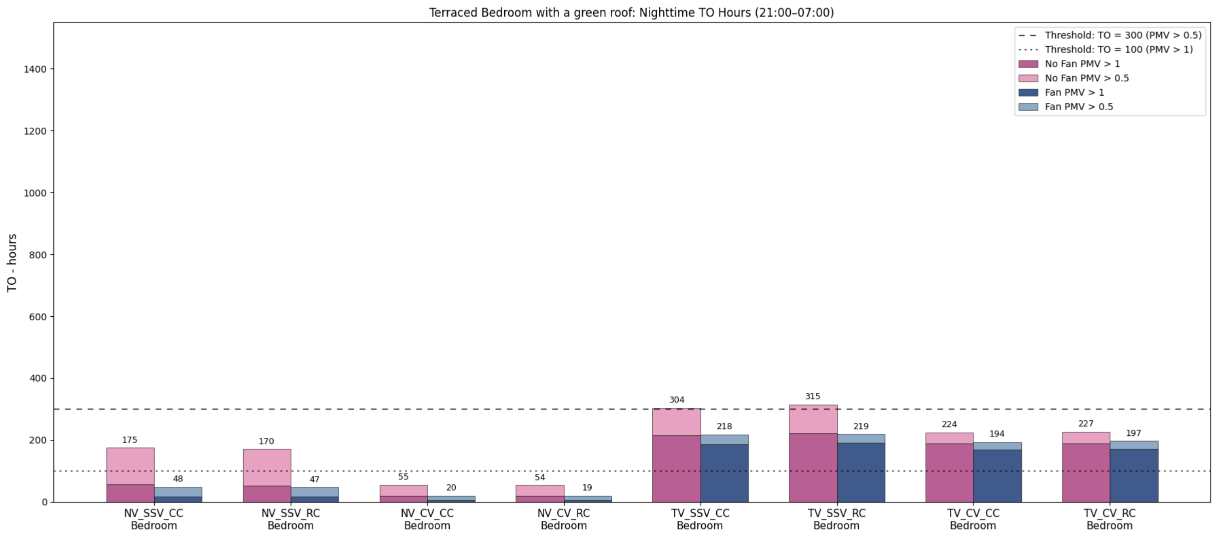
5.8.1



5.8.2

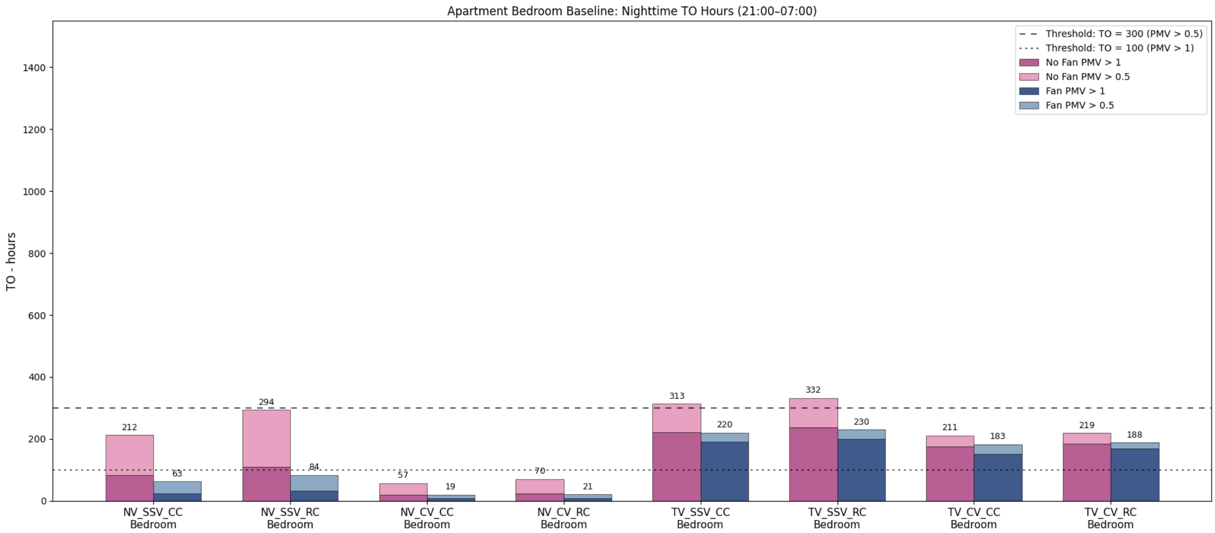


5.8.3

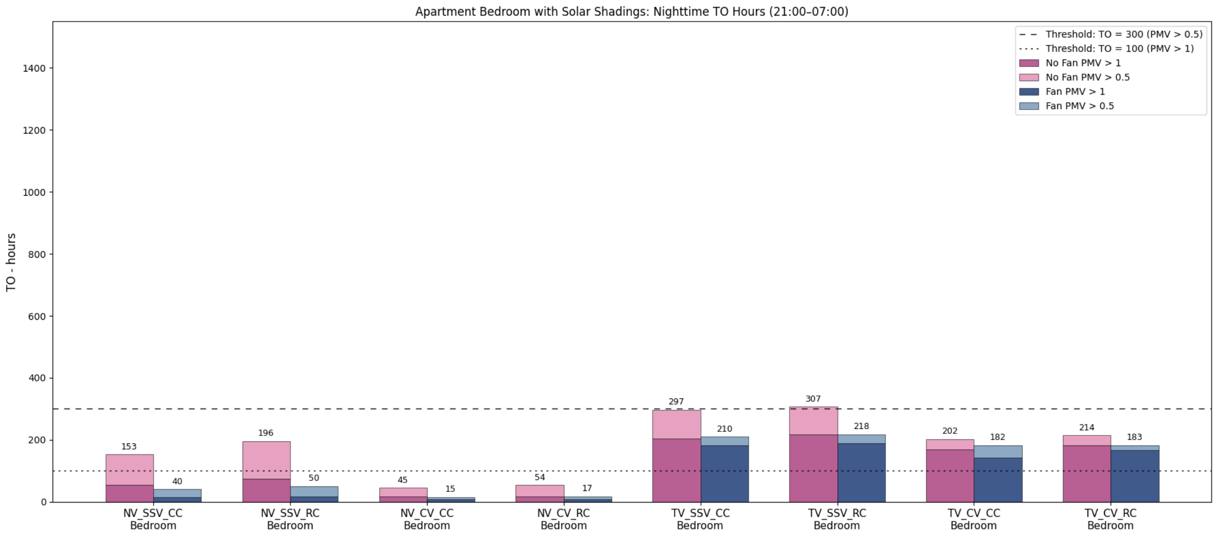


5.9 TO-hours (PMV>0.5 & PMV>1) during 21:00 - 07:00 in the Bedroom - Apartment

5.9.1

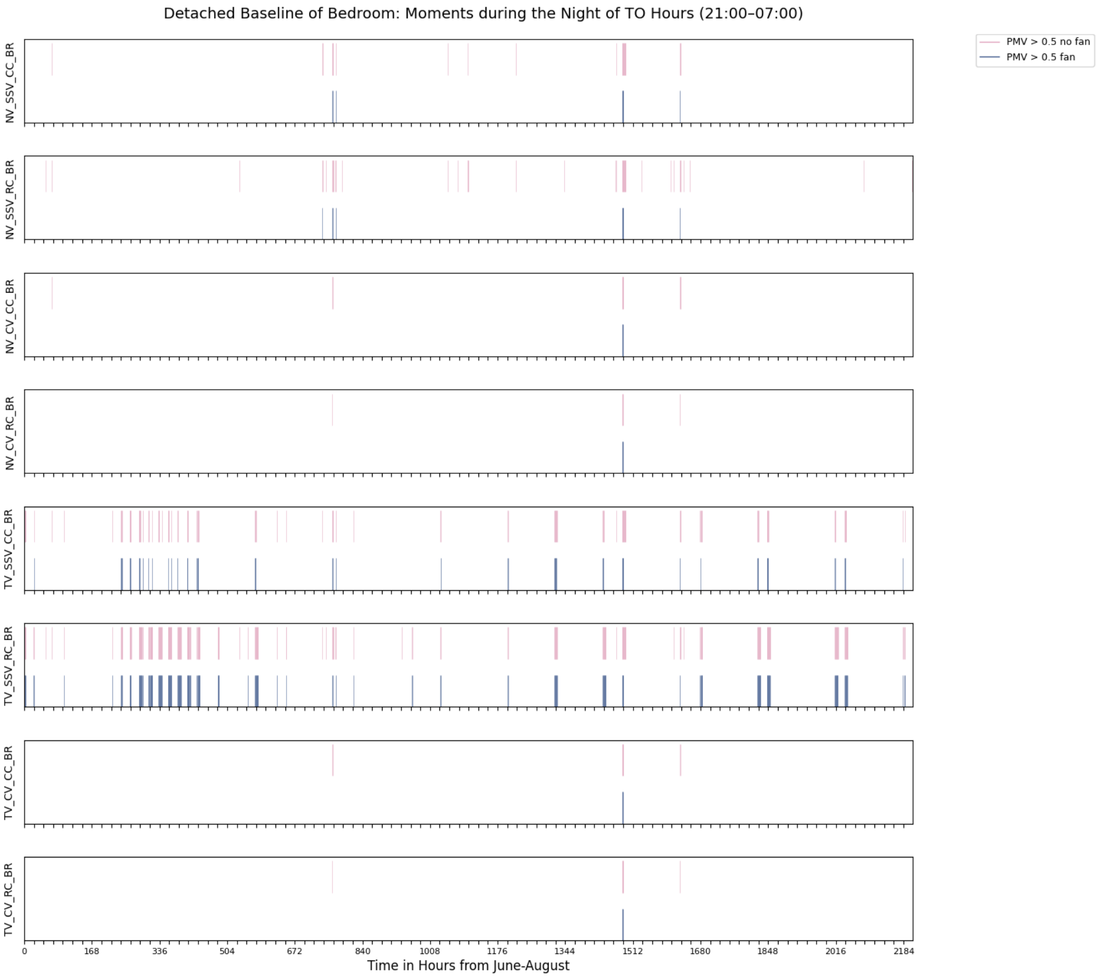


5.9.2

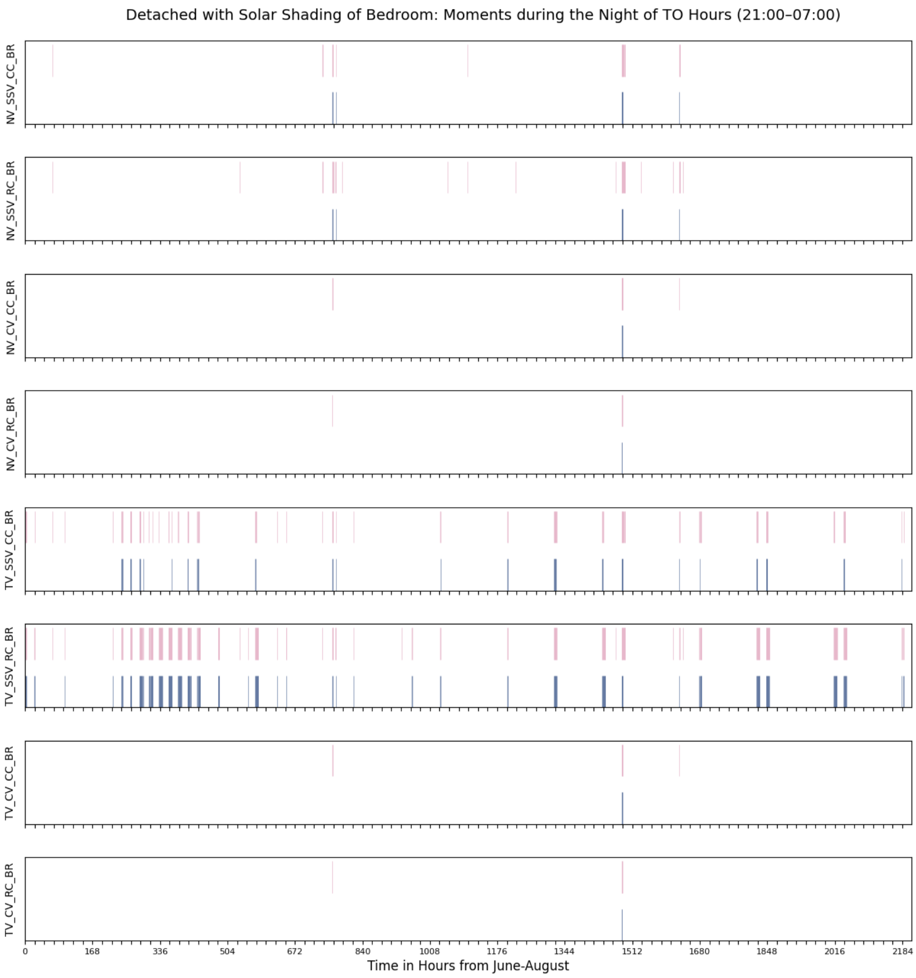


5.10 Hourly Exceedance of PMV>0.5 from 21:00-07:00 in the Bedroom - Detached

5.10.1

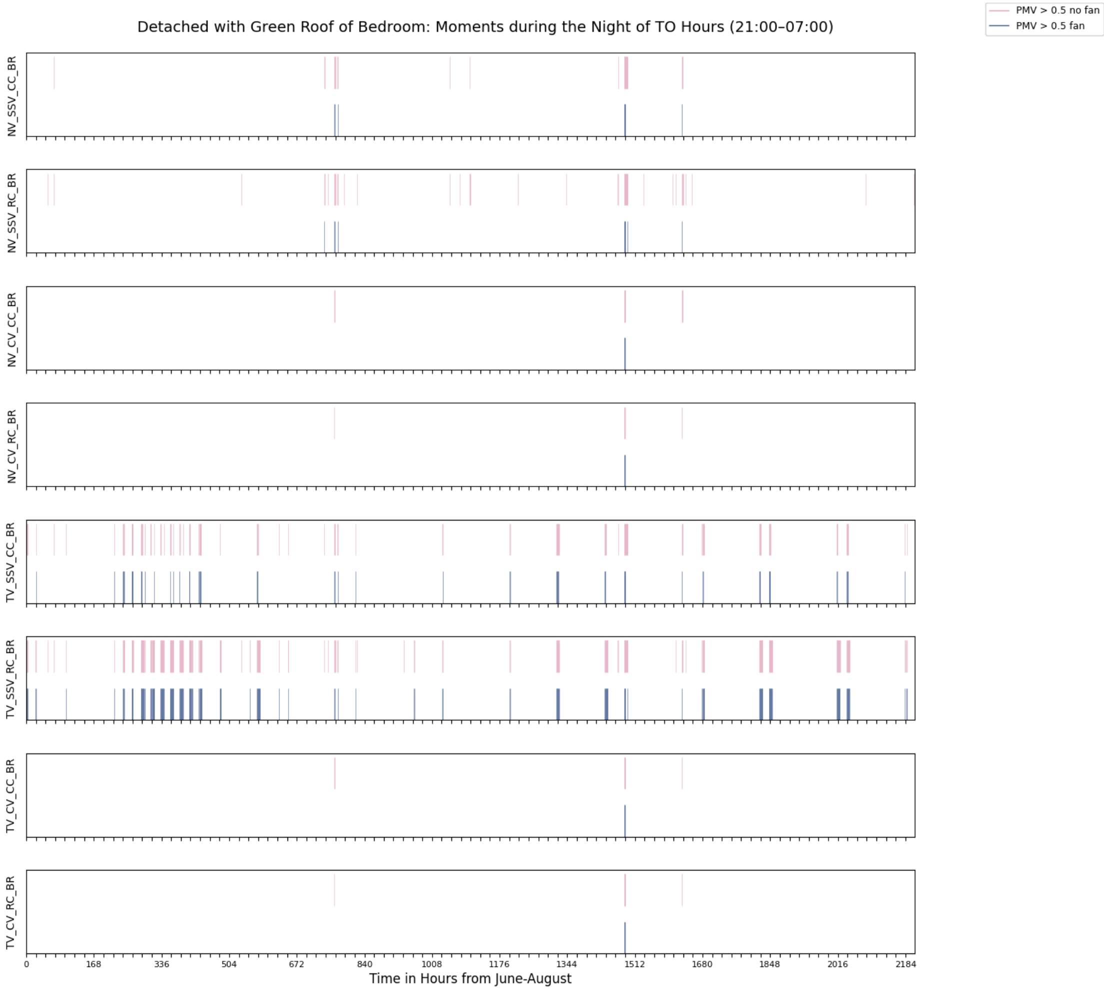


5.10.2



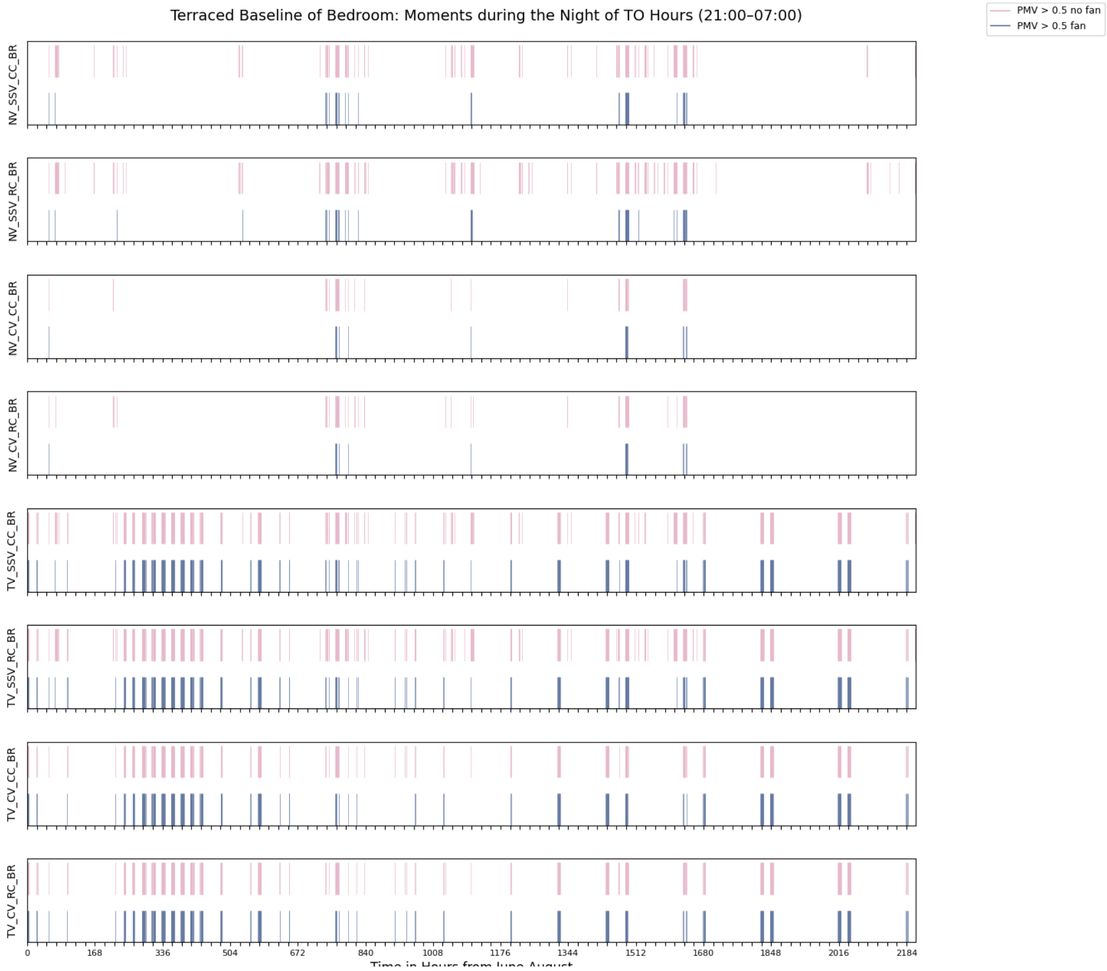
5.10 Hourly Exceedance of PMV>0.5 from 21:00-07:00 in the Bedroom - Detached

5.10.3

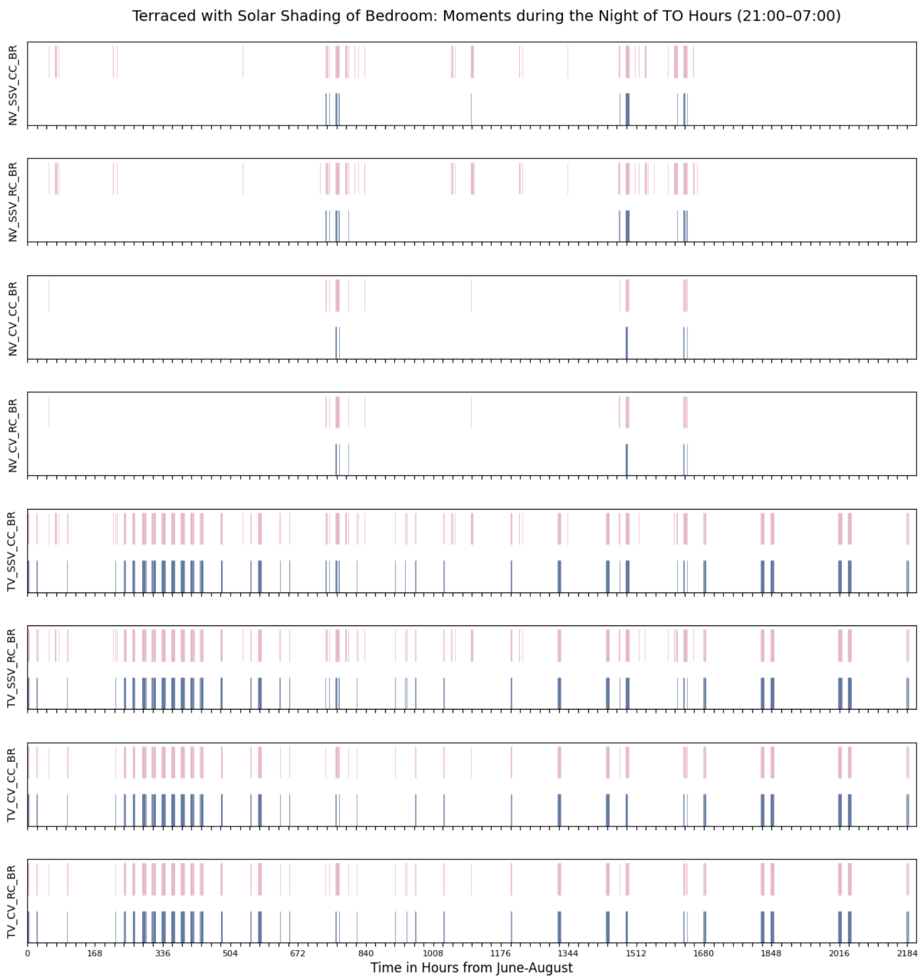


5.11 Hourly Exceedance of PMV>0.5 from 21:00-07:00 in the Bedroom - Terraced

5.11.1

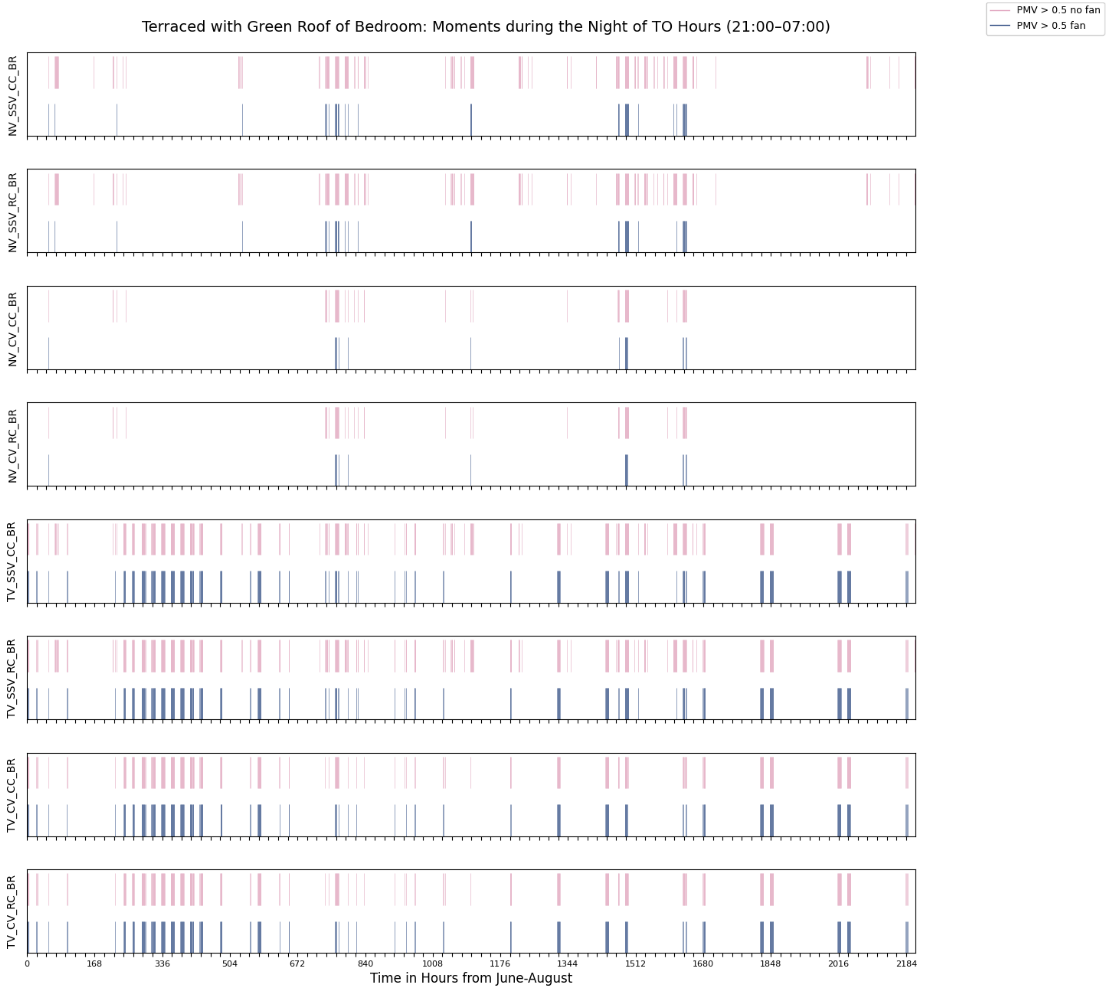


5.11.2



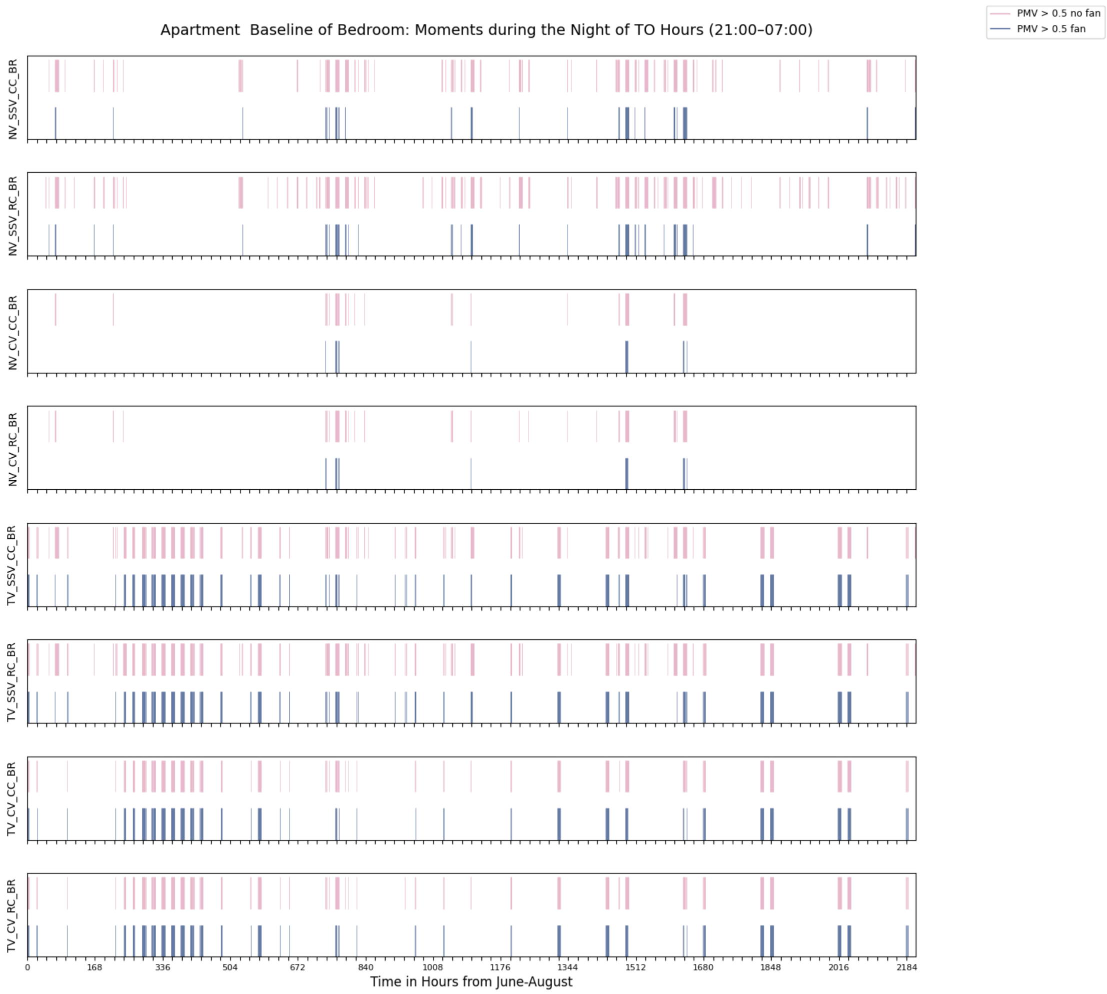
5.11 Hourly Exceedance of PMV>0.5 from 21:00-07:00 in the Bedroom - Terraced

5.11.3

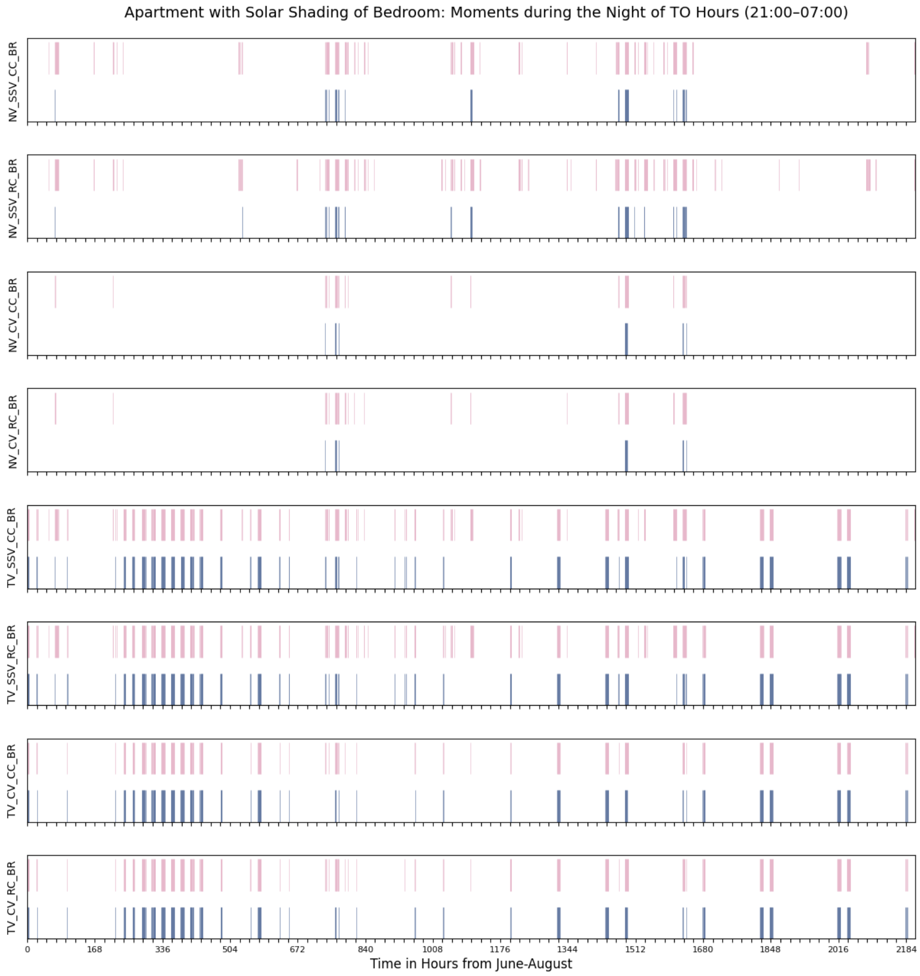


5.12 Hourly Exceedance of PMV>0.5 from 21:00-07:00 in the Bedroom - Apartment

5.12.1

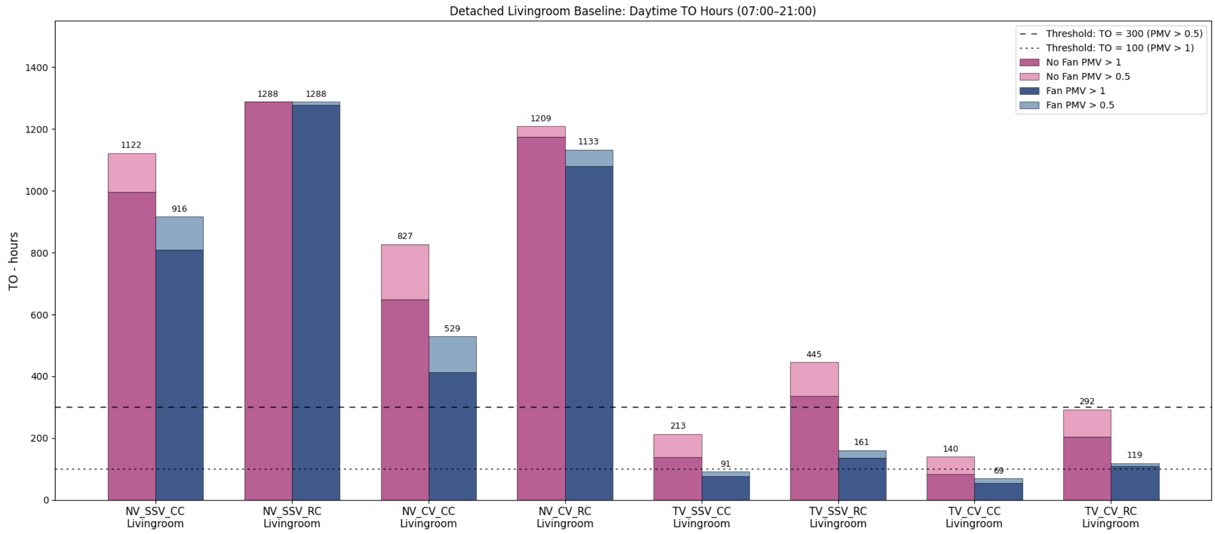


5.12.2

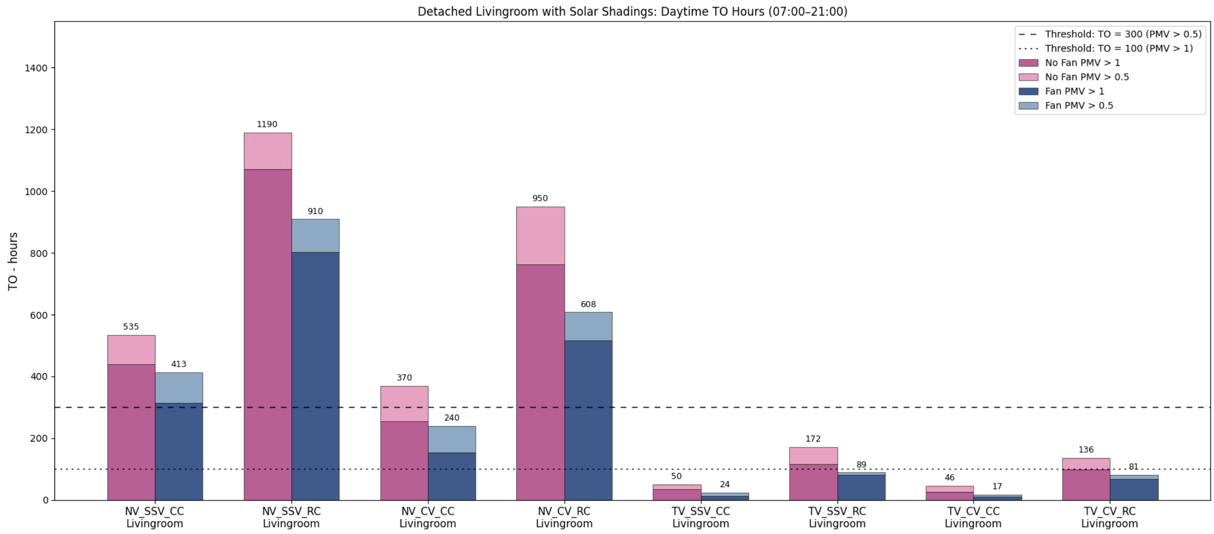


5.13 TO Exceedance (PMV>0.5 & PMV>1) during 07:00 - 21:00 in the Livingroom - Detached

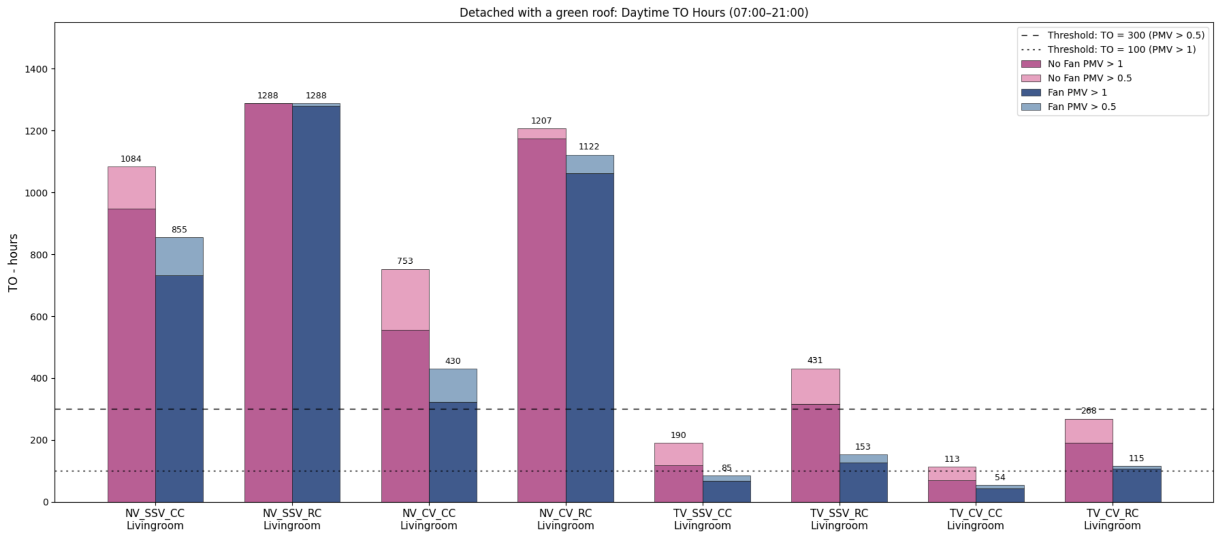
5.13.1



5.13.2

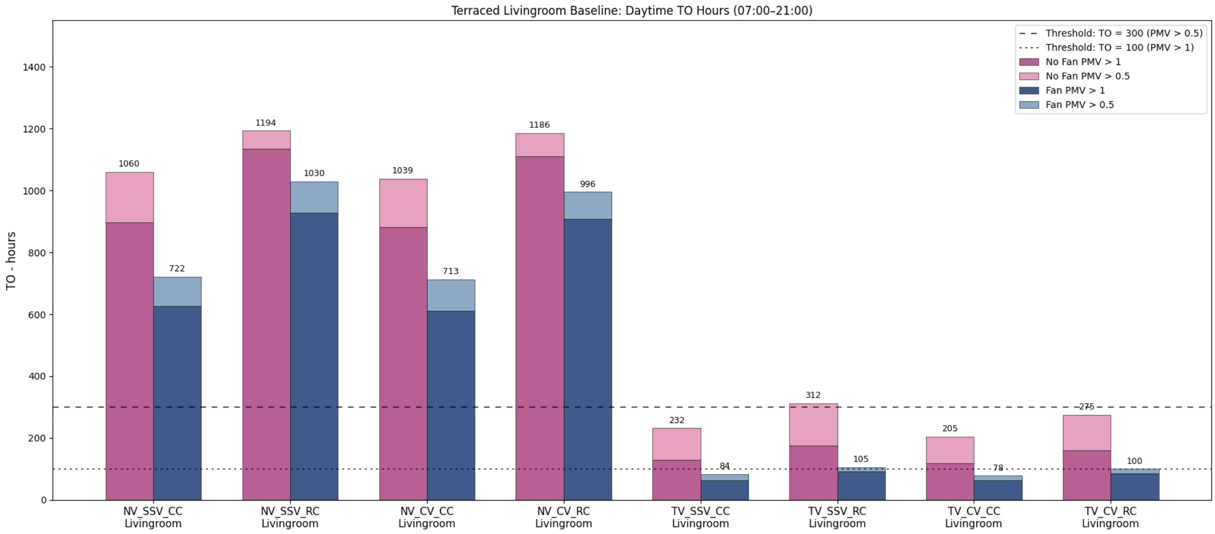


5.13.3

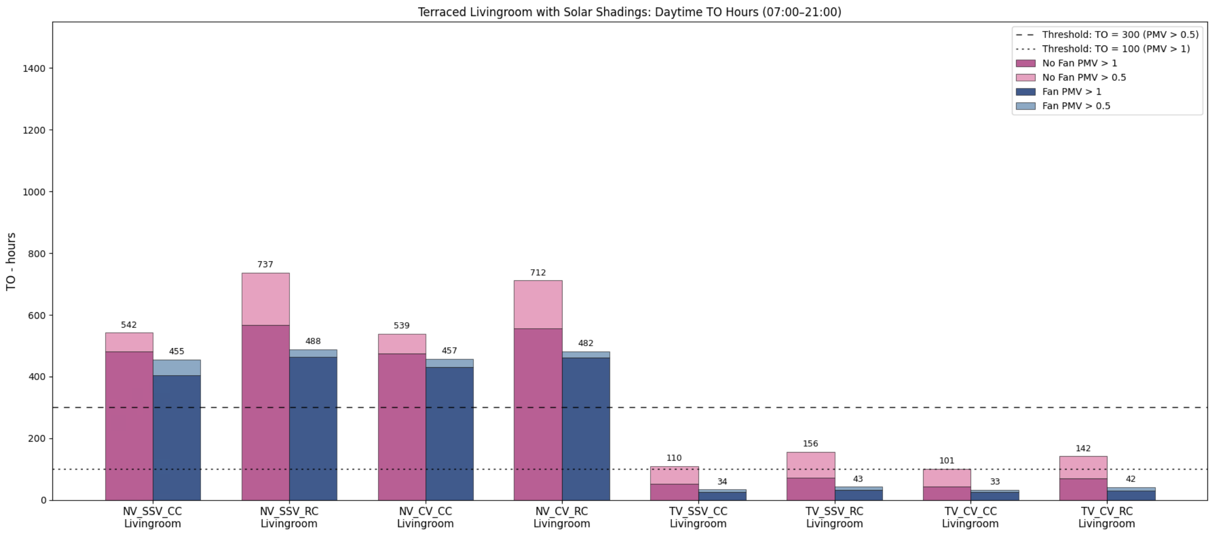


5.14 TO Exceedance (PMV>0.5 & PMV>1) during 07:00 - 21:00 in the Livingroom - Terraced

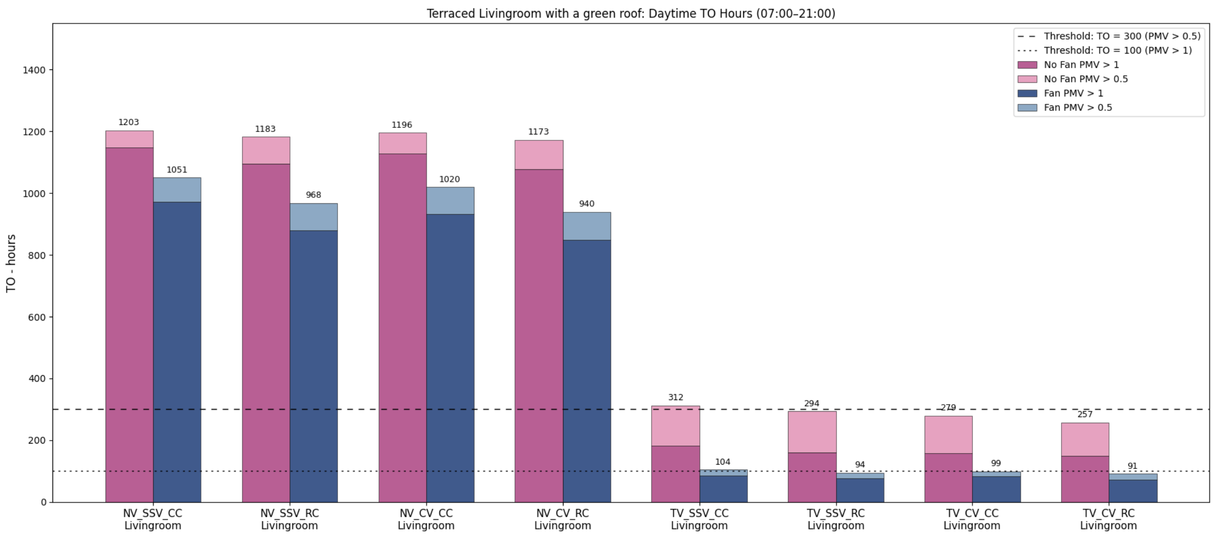
5.14.1



5.14.2

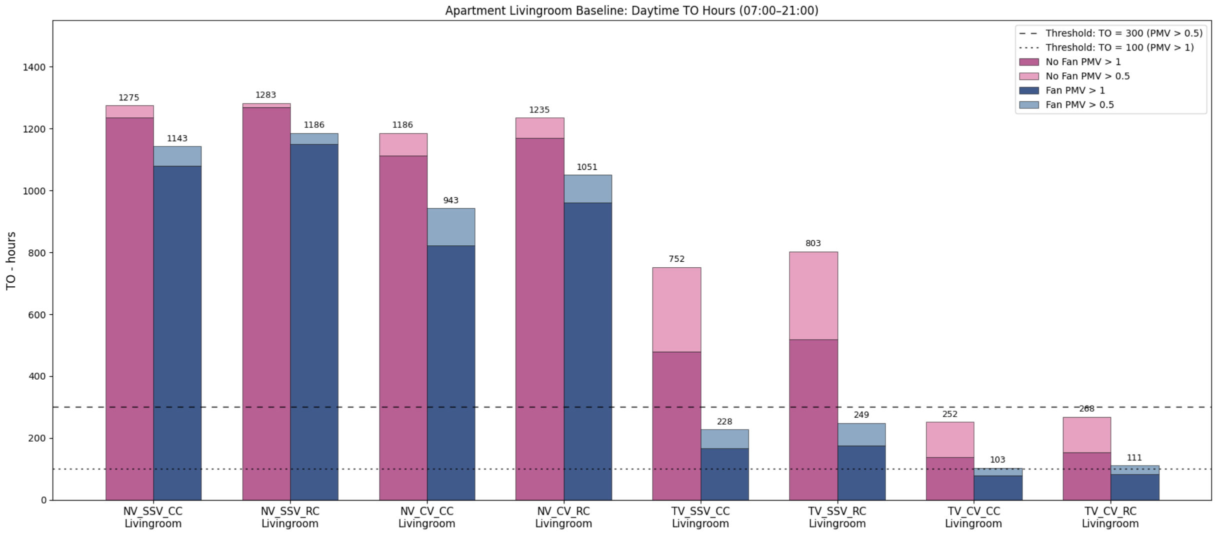


5.14.2

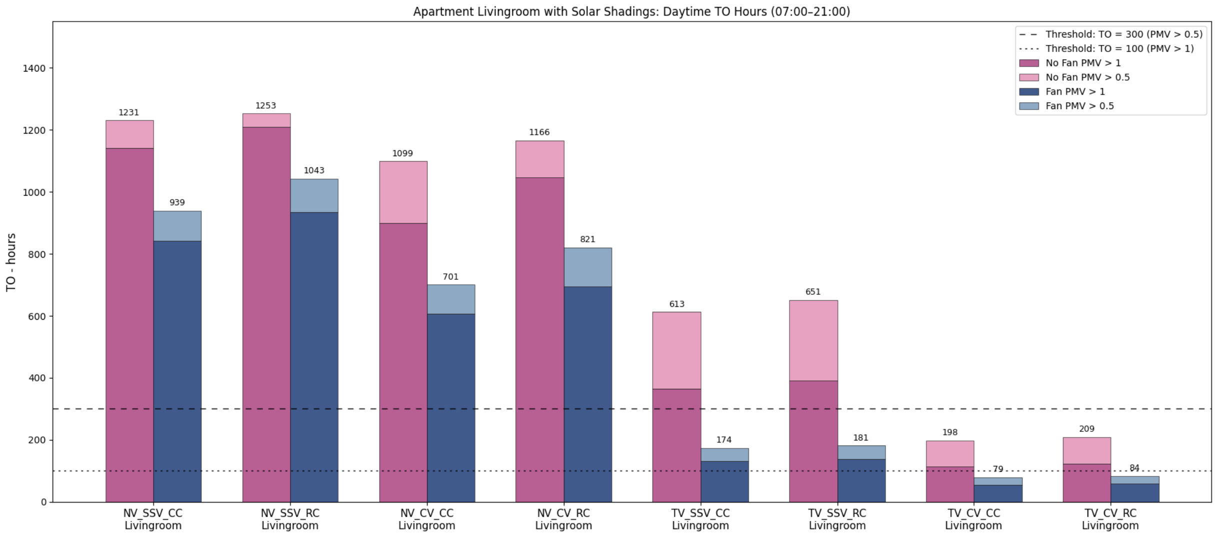


5.15 TO Exceedance (PMV>0.5 & PMV>1) during 07:00 - 21:00 in the Livingroom - Apartment

5.15.1



5.15.2



5.16 TO Exceedance during Night for Bedroom and Day for the Livingroom - Detached

Detached		Baseline: Single-Sided Ventilation, Current Construction Rvalue = 0.15 - 2,50	Baseline: Single-Sided Ventilation, Renovated Construction Rvalue = 1.70 - 3,50	Baseline: Cross Ventilation, Current Construction Rvalue = 0.15 - 2,50	Baseline: Cross Ventilation, Renovated Construction Rvalue = 1.70 - 3,50	Baseline & Ceiling Fans: Single-Sided Ventilation, Current Construction Rvalue = 0.15 - 2,50	Baseline & Ceiling Fans: Single-Sided Ventilation, Renovated Construction Rvalue = 1.70 - 3,50	Baseline & Ceiling Fans: Cross Ventilation, Current Construction Rvalue = 0.15 - 2,50	Baseline & Ceiling Fans: Cross Ventilation, Renovated Construction Rvalue = 1.70 - 3,50
Night Ventilation from 21:00 - 07:00	Bedroom	**24**	**42**	**10**	**5**	**8**	**9**	**3**	**3**
	Livingroom	1122	1288	827	1209	916	1288	529	1133
Temperature based Ventilation 15°C < $T_{outside}$ < 27°C	Bedroom	**109**	202	**8**	**6**	**61**	175	**3**	**3**
	Livingroom	213	445	**140**	292	**91**	161	**69**	**119**

Detached		Shadings: Single-Sided Ventilation, Current Construction Rvalue = 0.15 - 2,50	Shadings: Single-Sided Ventilation, Renovated Construction Rvalue = 1.70 - 3,50	Shadings: Cross Ventilation, Current Construction Rvalue = 0.15 - 2,50	Shadings: Cross Ventilation, Renovated Construction Rvalue = 1.70 - 3,50	Shadings & Ceiling Fans: Single-Sided Ventilation, Current Construction Rvalue = 0.15 - 2,50	Shadings & Ceiling Fans: Single-Sided Ventilation, Renovated Construction Rvalue = 1.70 - 3,50	Shadings & Ceiling Fans: Cross Ventilation, Current Construction Rvalue = 0.15 - 2,50	Shadings & Ceiling Fans: Cross Ventilation, Renovated Construction Rvalue = 1.70 - 3,50
Night Ventilation from 21:00 - 07:00	Bedroom	**20**	**31**	**7**	**4**	**8**	**8**	**3**	**2**
	Livingroom	535	1190	370	950	413	910	240	608
Temperature based Ventilation 15°C < $T_{outside}$ < 27°C	Bedroom	**100**	197	**7**	**4**	**52**	175	**3**	**2**
	Livingroom	**50**	172	**46**	136	**24**	89	**17**	**81**

Detached		Green roof: Single-Sided Ventilation, Current Construction Rvalue = 0.15 - 2,50	Green roof: Single-Sided Ventilation, Renovated Construction Rvalue = 1.70 - 3,50	Green roof: Cross Ventilation, Current Construction Rvalue = 0.15 - 2,50	Green roof: Cross Ventilation, Renovated Construction Rvalue = 1.70 - 3,50	Green roof & Ceiling Fans: Single-Sided Ventilation, Current Construction Rvalue = 0.15 - 2,50	Green roof & Ceiling Fans: Single-Sided Ventilation, Renovated Construction Rvalue = 1.70 - 3,50	Green roof & Ceiling Fans: Cross Ventilation, Current Construction Rvalue = 0.15 - 2,50	Green roof & Ceiling Fans: Cross Ventilation, Renovated Construction Rvalue = 1.70 - 3,50
Night Ventilation from 21:00 - 07:00	Bedroom	**25**	**44**	**9**	**5**	**8**	**10**	**3**	**3**
	Livingroom	1084	1288	753	1207	855	1288	430	1122
Temperature based Ventilation 15°C < $T_{outside}$ < 27°C	Bedroom	**115**	204	**7**	**6**	**66**	176	**3**	**3**
	Livingroom	190	431	**113**	268	**85**	153	**54**	**115**

The tables present the number of TO hours—defined as the total summer hours during which PMV > 0.5 is exceeded—for each combination of cooling strategies for the bedroom during night (21:00-07:00) and the livingroom during the day (07:00-21:00). To ensure consistency across all tables in this thesis, the maximum value for the red color scale is set at 1550 TO hours. This allows for a uniform visual comparison of performance. Values shown in bold blue indicate compliance with Dutch guidelines, meaning that PMV > 0.5 is exceeded for no more than 300 hours, and PMV > 1 is exceeded for no more than 100 hours.

1550 TO Hours

0

X = complience

5.17 TO Exceedance during Night for Bedroom and Day for the Livingroom - Terraced

Terraced		Baseline				Baseline & Ceiling Fans			
		Single-Sided Ventilation		Cross Ventilation		Single-Sided Ventilation		Cross Ventilation	
		Current Construction Rvalue = 0.15 - 2,50	Renovated Construction Rvalue = 1.70 - 3,50	Current Construction Rvalue = 0.15 - 2,50	Renovated Construction Rvalue = 1.70 - 3,50	Current Construction Rvalue = 0.15 - 2,50	Renovated Construction Rvalue = 1.70 - 3,50	Current Construction Rvalue = 0.15 - 2,50	Renovated Construction Rvalue = 1.70 - 3,50
Night Ventilation from 21:00 - 07:00	Bedroom	**138**	**180**	**45**	**58**	**39**	**49**	**19**	**19**
	Livingroom	1060	1194	1039	1186	722	1030	713	996
Temperature based Ventilation 15°C < $T_{outside}$ < 27°C	Bedroom	292	316	214	226	214	219	188	195
	Livingroom	232	312	205	275	**84**	**105**	**78**	**100**

Terraced		Shadings				Shadings & Ceiling Fans			
		Single-Sided Ventilation		Cross Ventilation		Single-Sided Ventilation		Cross Ventilation	
		Current Construction Rvalue = 0.15 - 2,50	Renovated Construction Rvalue = 1.70 - 3,50	Current Construction Rvalue = 0.15 - 2,50	Renovated Construction Rvalue = 1.70 - 3,50	Current Construction Rvalue = 0.15 - 2,50	Renovated Construction Rvalue = 1.70 - 3,50	Current Construction Rvalue = 0.15 - 2,50	Renovated Construction Rvalue = 1.70 - 3,50
Night Ventilation from 21:00 - 07:00	Bedroom	**94**	**106**	**33**	**34**	**27**	**29**	**12**	**13**
	Livingroom	546	745	542	719	455	488	457	482
Temperature based Ventilation 15°C < $T_{outside}$ < 27°C	Bedroom	262	267	206	212	201	207	183	185
	Livingroom	**117**	**174**	**108**	**157**	**35**	**47**	**34**	**45**

Terraced		Green roof				Green roof & Ceiling Fans			
		Single-Sided Ventilation		Cross Ventilation		Single-Sided Ventilation		Cross Ventilation	
		Current Construction Rvalue = 0.15 - 2,50	Renovated Construction Rvalue = 1.70 - 3,50	Current Construction Rvalue = 0.15 - 2,50	Renovated Construction Rvalue = 1.70 - 3,50	Current Construction Rvalue = 0.15 - 2,50	Renovated Construction Rvalue = 1.70 - 3,50	Current Construction Rvalue = 0.15 - 2,50	Renovated Construction Rvalue = 1.70 - 3,50
Night Ventilation from 21:00 - 07:00	Bedroom	**175**	**170**	**55**	**54**	**48**	**47**	**20**	**19**
	Livingroom	1203	1183	1196	1173	1051	968	1020	940
Temperature based Ventilation 15°C < $T_{outside}$ < 27°C	Bedroom	304	315	224	227	218	219	194	197
	Livingroom	312	294	279	257	**104**	**94**	**99**	**91**

The tables present the number of TO hours—defined as the total summer hours during which PMV > 0.5 is exceeded—for each combination of cooling strategies for the bedroom during night (21:00-07:00) and the livingroom during the day (07:00-21:00). To ensure consistency across all tables in this thesis, the maximum value for the red color scale is set at 1550 TO hours. This allows for a uniform visual comparison of performance. Values shown in bold blue indicate compliance with Dutch guidelines, meaning that PMV > 0.5 is exceeded for no more than 300 hours, and PMV > 1 is exceeded for no more than 100 hours.

1550 TO Hours
0
X = complience

5.18 TO Exceedance during Night for Bedroom and Day for the Livingroom - Apartment

Apartment		Baseline: Single-Sided Ventilation, Current Construction Rvalue = 0.15 - 2,50	Baseline: Single-Sided Ventilation, Renovated Construction Rvalue = 1.70 - 3,50	Baseline: Cross Ventilation, Current Construction Rvalue = 0.15 - 2,50	Baseline: Cross Ventilation, Renovated Construction Rvalue = 1.70 - 3,50	Baseline & Ceiling Fans: Single-Sided Ventilation, Current Construction Rvalue = 0.15 - 2,50	Baseline & Ceiling Fans: Single-Sided Ventilation, Renovated Construction Rvalue = 1.70 - 3,50	Baseline & Ceiling Fans: Cross Ventilation, Current Construction Rvalue = 0.15 - 2,50	Baseline & Ceiling Fans: Cross Ventilation, Renovated Construction Rvalue = 1.70 - 3,50
Night Ventilation from 21:00 - 07:00	Bedroom	**212**	**294**	**57**	**70**	**63**	**84**	**19**	**21**
	Livingroom	1275	1283	1186	1235	1143	1186	943	1051
Temperature based Ventilation 15°C < $T_{outside}$ < 27°C	Bedroom	313	332	211	219	220	230	183	188
	Livingroom	752	803	252	268	228	249	**103**	**111**

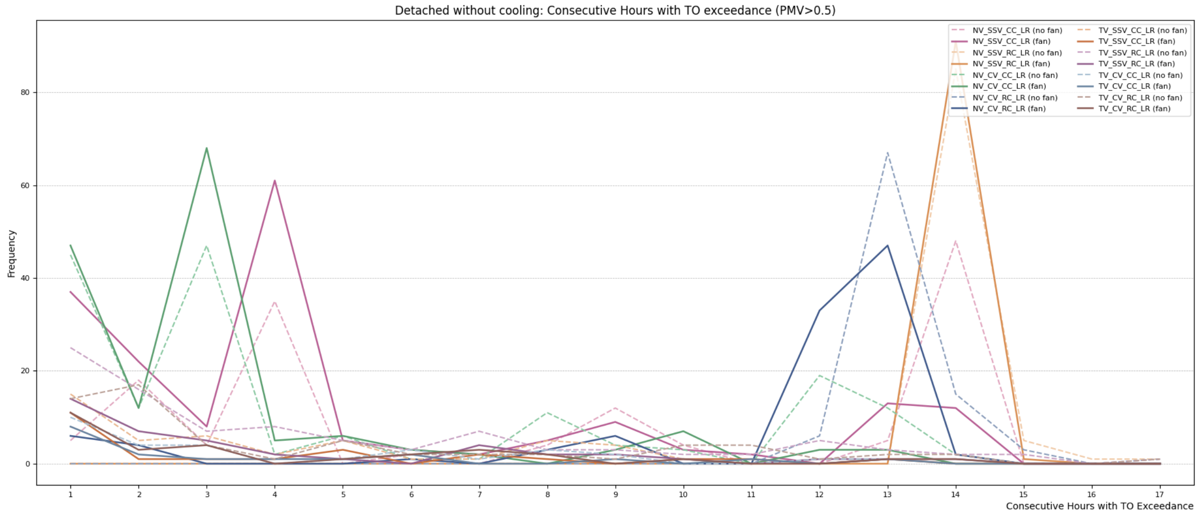
Apartment		Shadings: Single-Sided Ventilation, Current Construction Rvalue = 0.15 - 2,50	Shadings: Single-Sided Ventilation, Renovated Construction Rvalue = 1.70 - 3,50	Shadings: Cross Ventilation, Current Construction Rvalue = 0.15 - 2,50	Shadings: Cross Ventilation, Renovated Construction Rvalue = 1.70 - 3,50	Shadings & Ceiling Fans: Single-Sided Ventilation, Current Construction Rvalue = 0.15 - 2,50	Shadings & Ceiling Fans: Single-Sided Ventilation, Renovated Construction Rvalue = 1.70 - 3,50	Shadings & Ceiling Fans: Cross Ventilation, Current Construction Rvalue = 0.15 - 2,50	Shadings & Ceiling Fans: Cross Ventilation, Renovated Construction Rvalue = 1.70 - 3,50
Night Ventilation from 21:00 - 07:00	Bedroom	**153**	**196**	**45**	**54**	**40**	**50**	**15**	**17**
	Livingroom	1231	1253	1099	1166	939	1043	701	821
Temperature based Ventilation 15°C < $T_{outside}$ < 27°C	Bedroom	297	307	202	214	210	218	182	183
	Livingroom	613	651	198	209	174	181	**79**	**84**

The tables present the number of TO hours—defined as the total summer hours during which PMV > 0.5 is exceeded—for each combination of cooling strategies for the bedroom during night (21:00-07:00) and the livingroom during the day (07:00-21:00). To ensure consistency across all tables in this thesis, the maximum value for the red color scale is set at 1550 TO hours. This allows for a uniform visual comparison of performance. Values shown in bold blue indicate compliance with Dutch guidelines, meaning that PMV > 0.5 is exceeded for no more than 300 hours, and PMV > 1 is exceeded for no more than 100 hours.

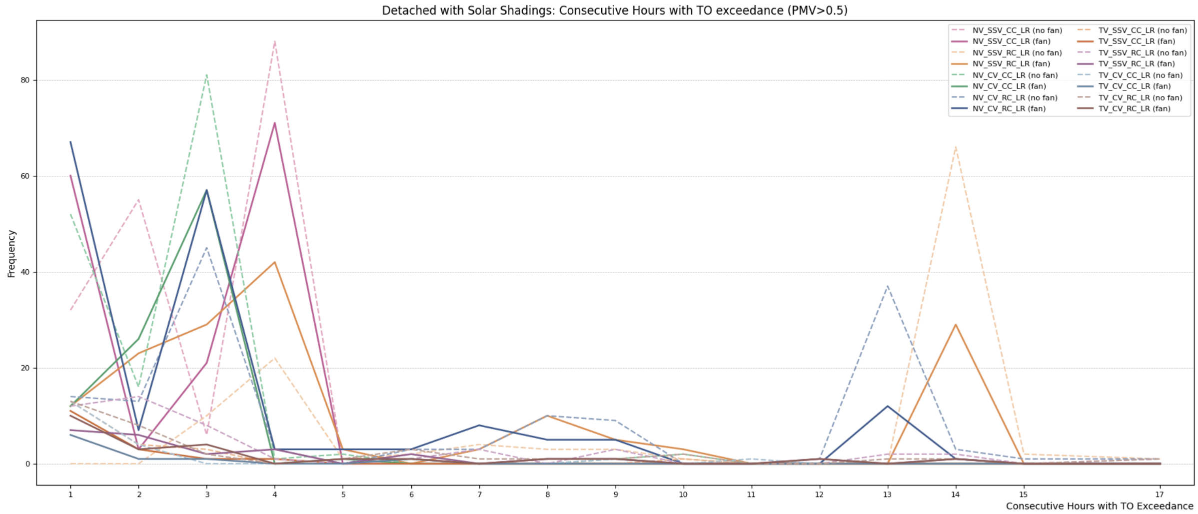
1550 TO Hours
0
X = complience

5.19 Consecutive Hours with TO Exceedance (PMV>0.5) in the Livingroom - Detached

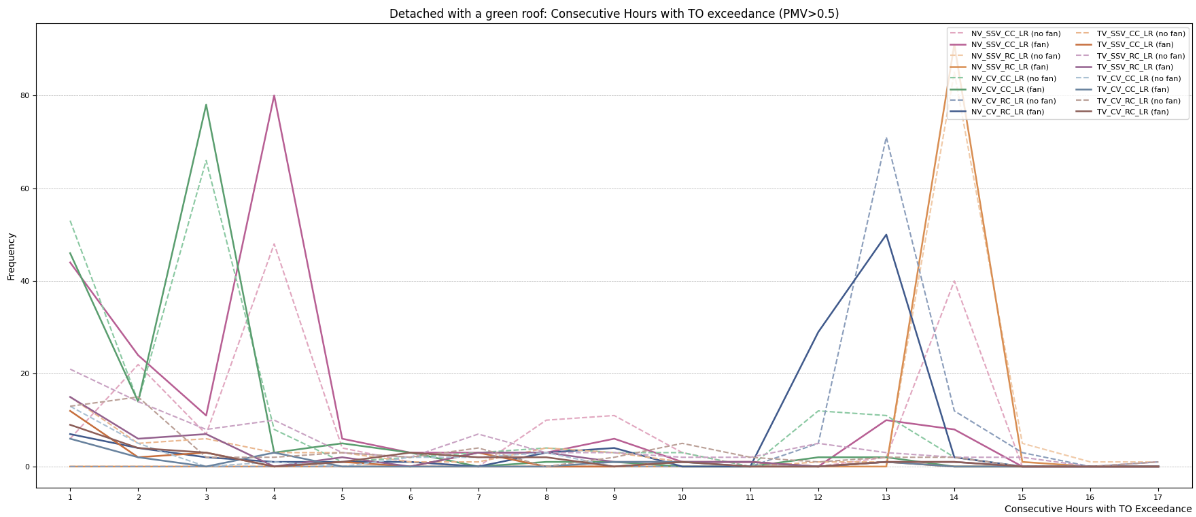
5.19.1



5.19.2

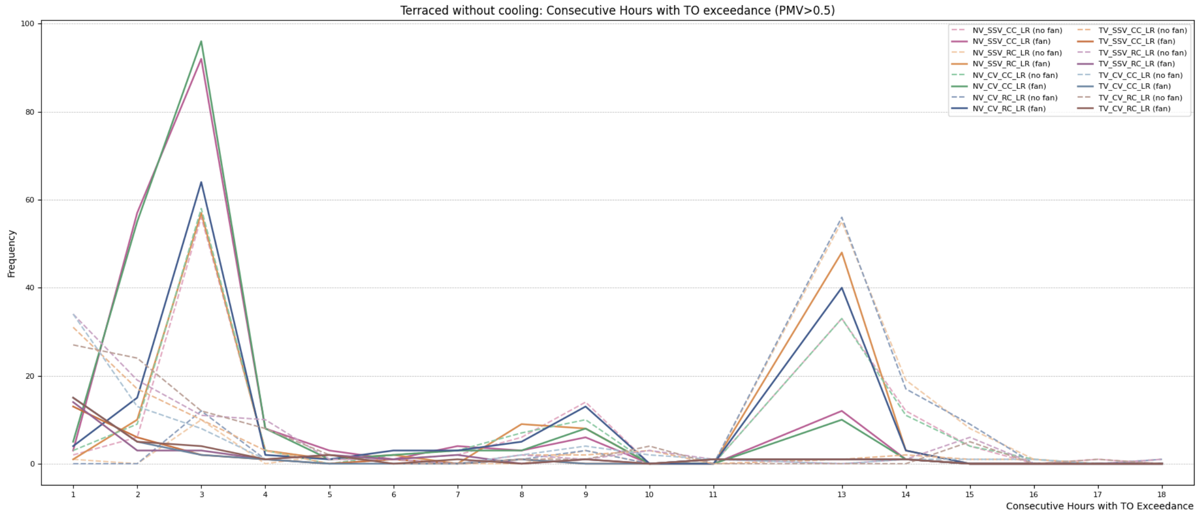


5.19.3

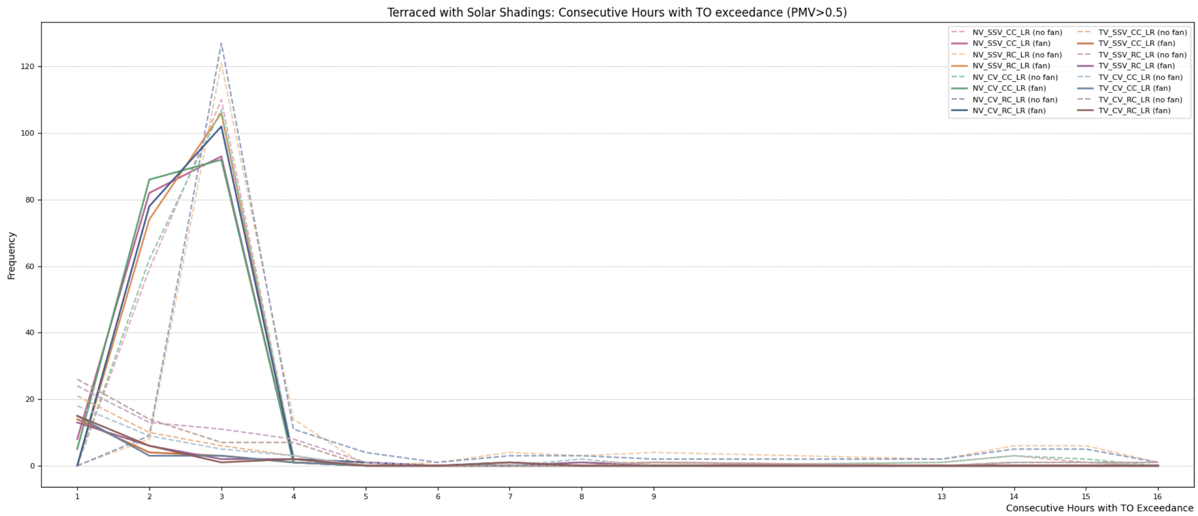


5.20 Consecutive Hours with TO Exceedance (PMV>0.5) in the Livingroom - Terraced

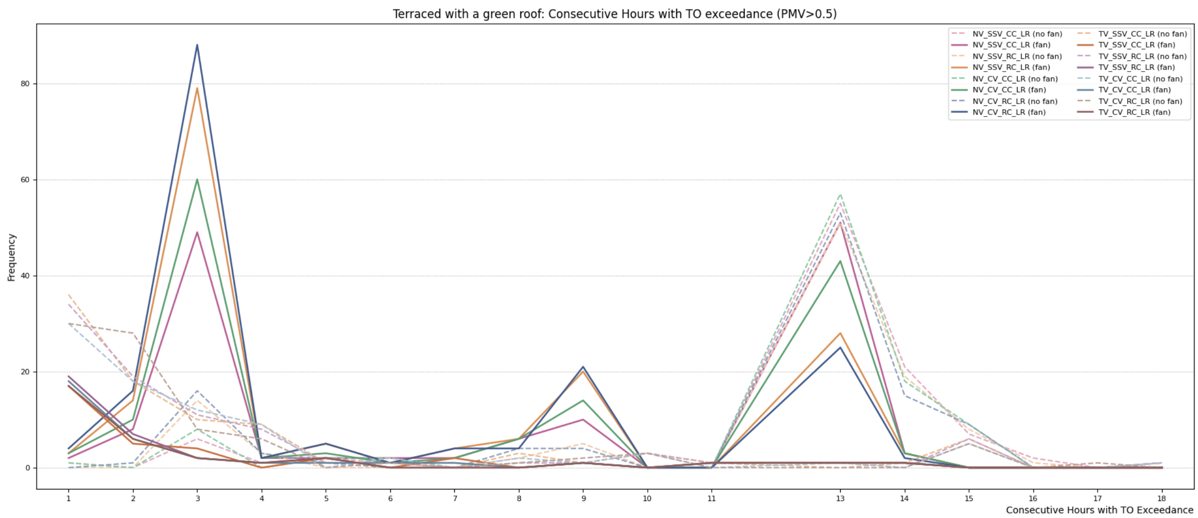
5.20.1



5.20.2

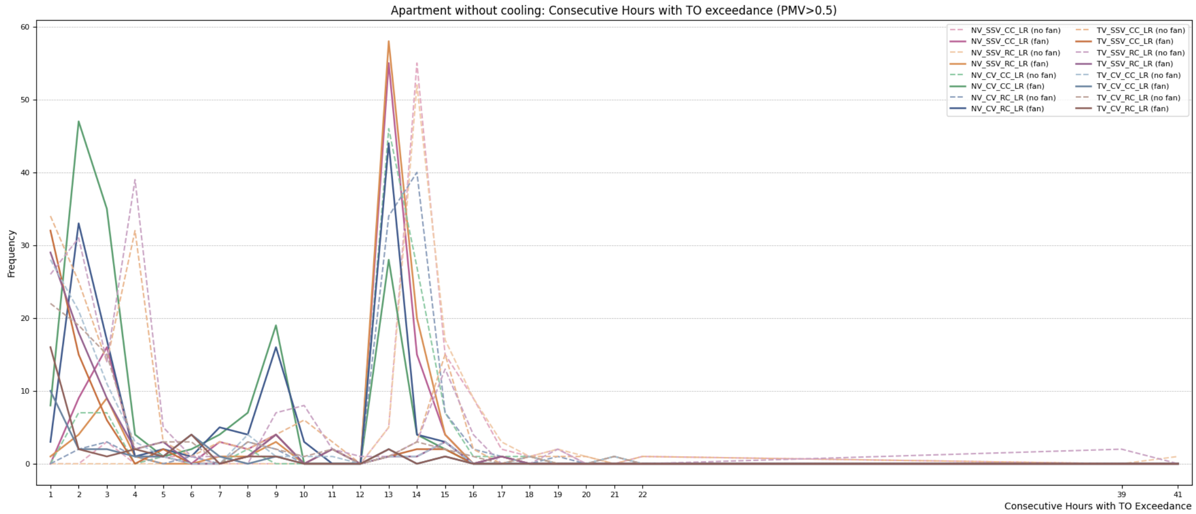


5.20.3

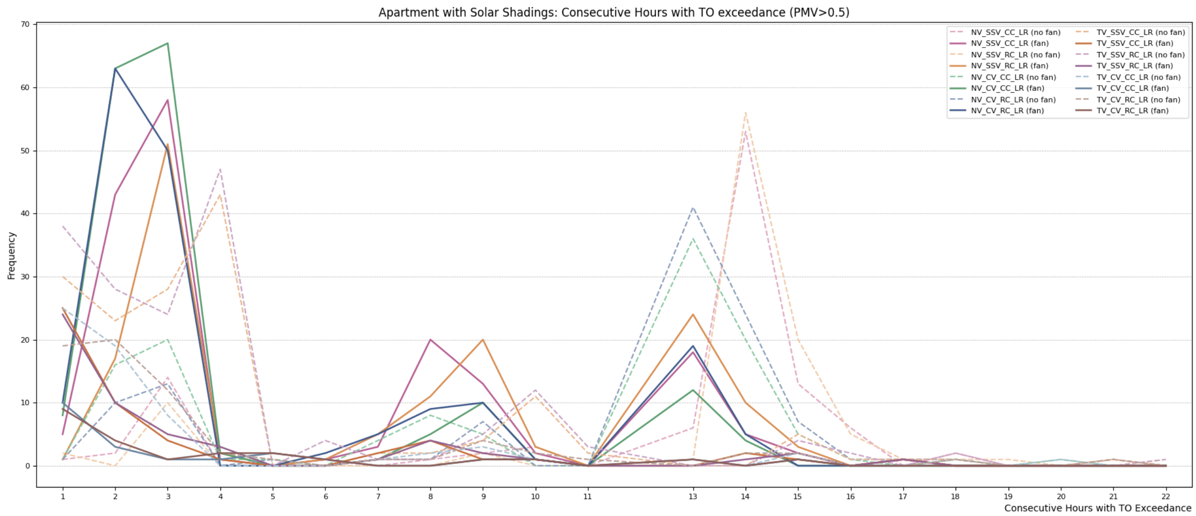


5.21 Consecutive Hours with TO Exceedance (PMV>0.5) in the Livingroom - Apartment

5.21.1

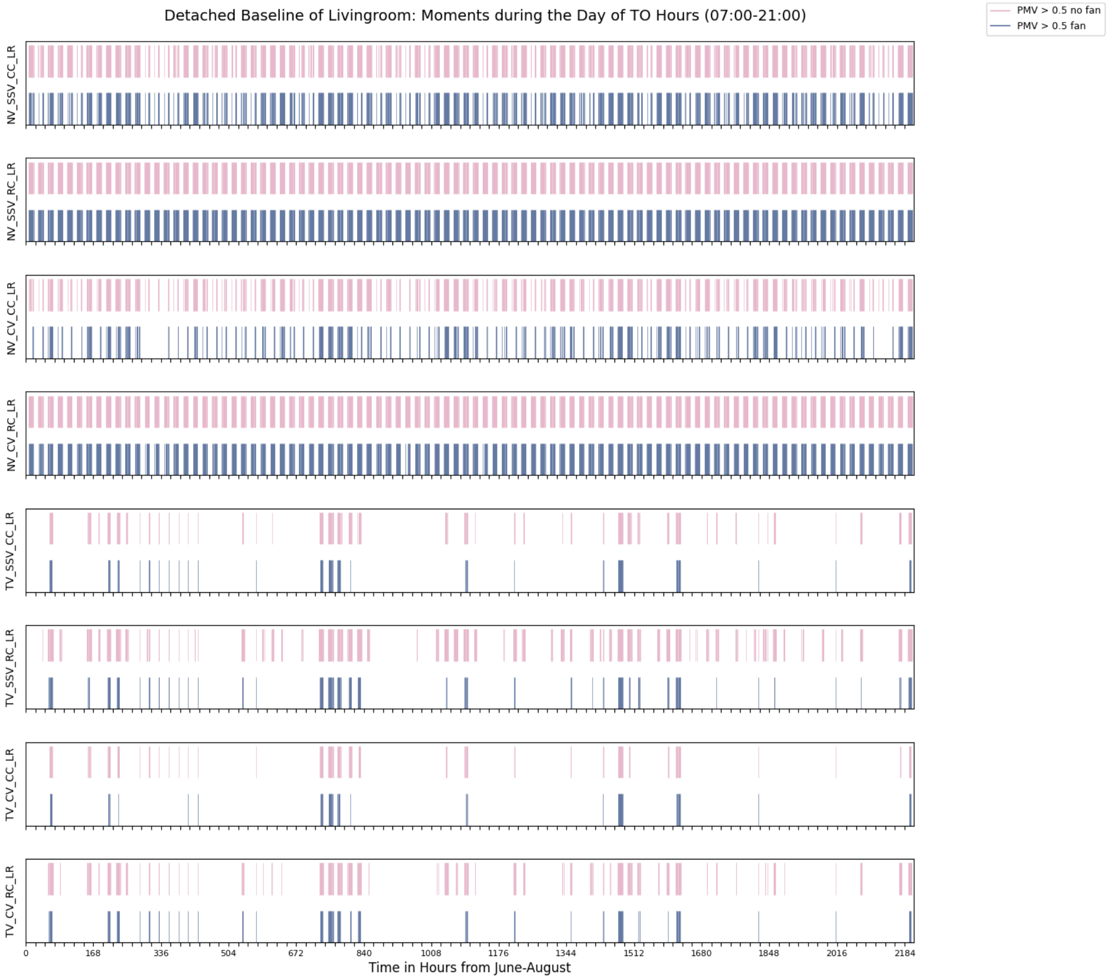


5.21.2

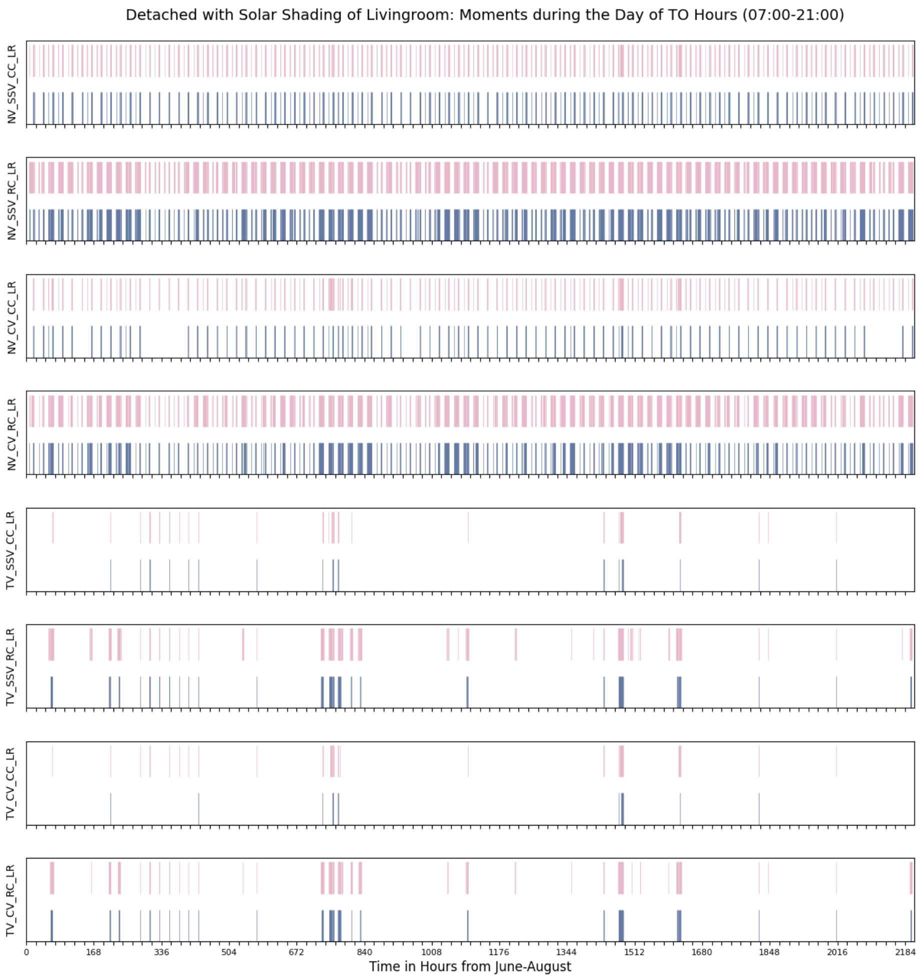


5.22 Hourly Exceedance of PMV>0.5 in the Livingroom - Detached

5.22.1

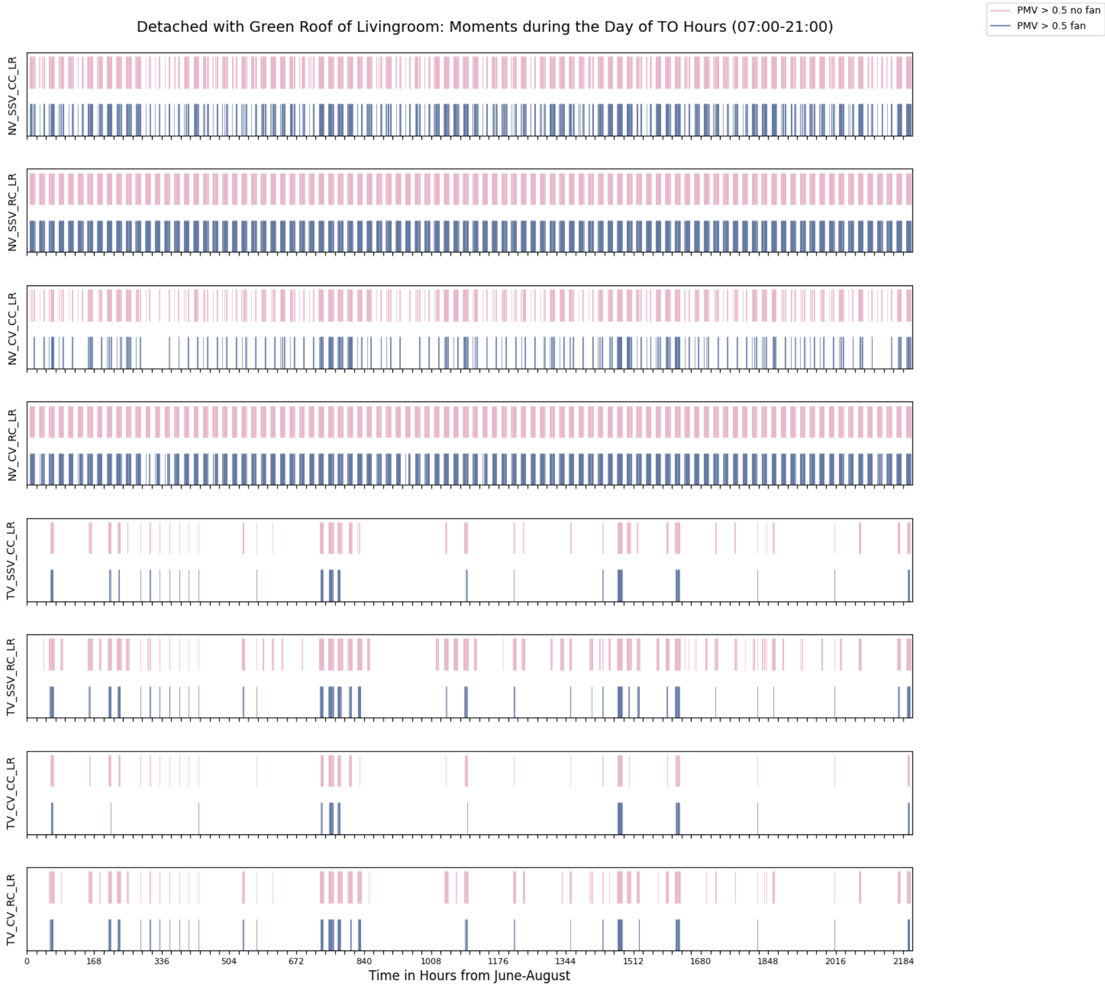


5.22.2



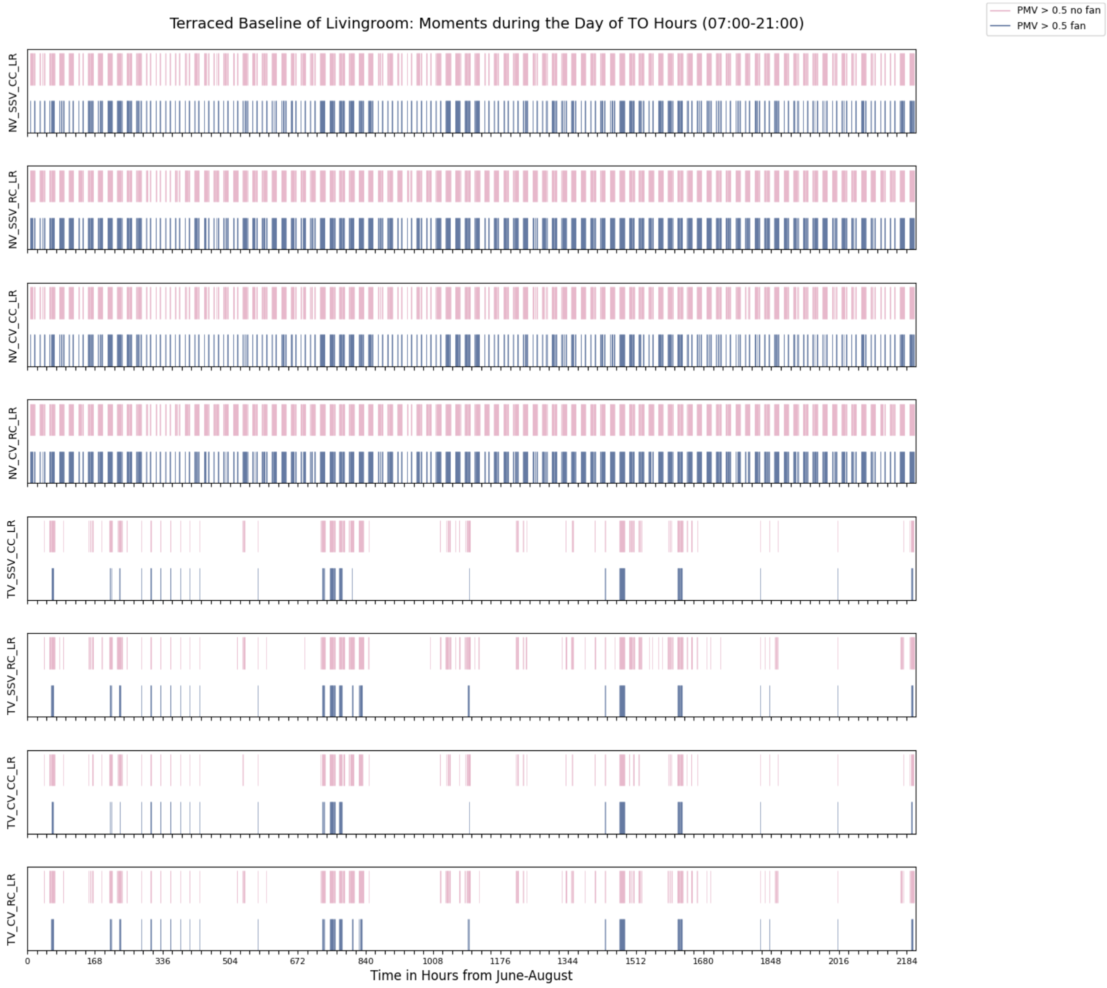
5.22 Hourly Exceedance of PMV>0.5 in the Livingroom - Detached

5.22.3

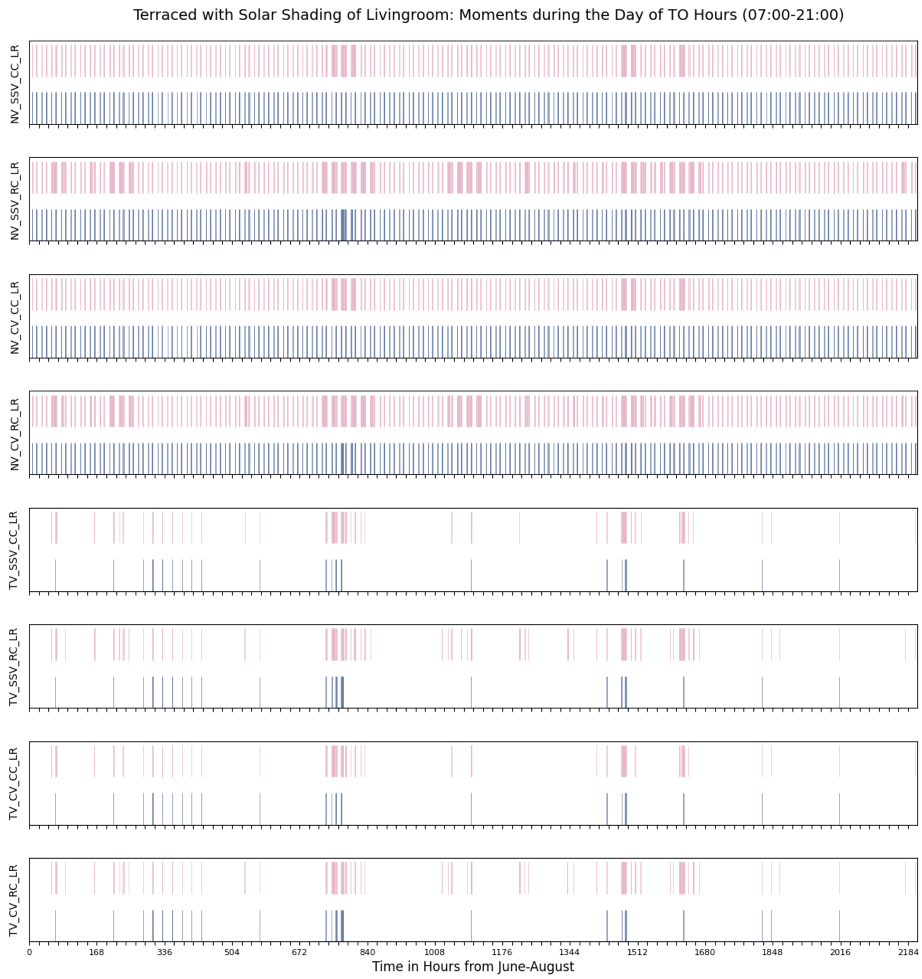


5.23 Hourly Exceedance of PMV>0.5 in the Livingroom -Terraced

5.23.1

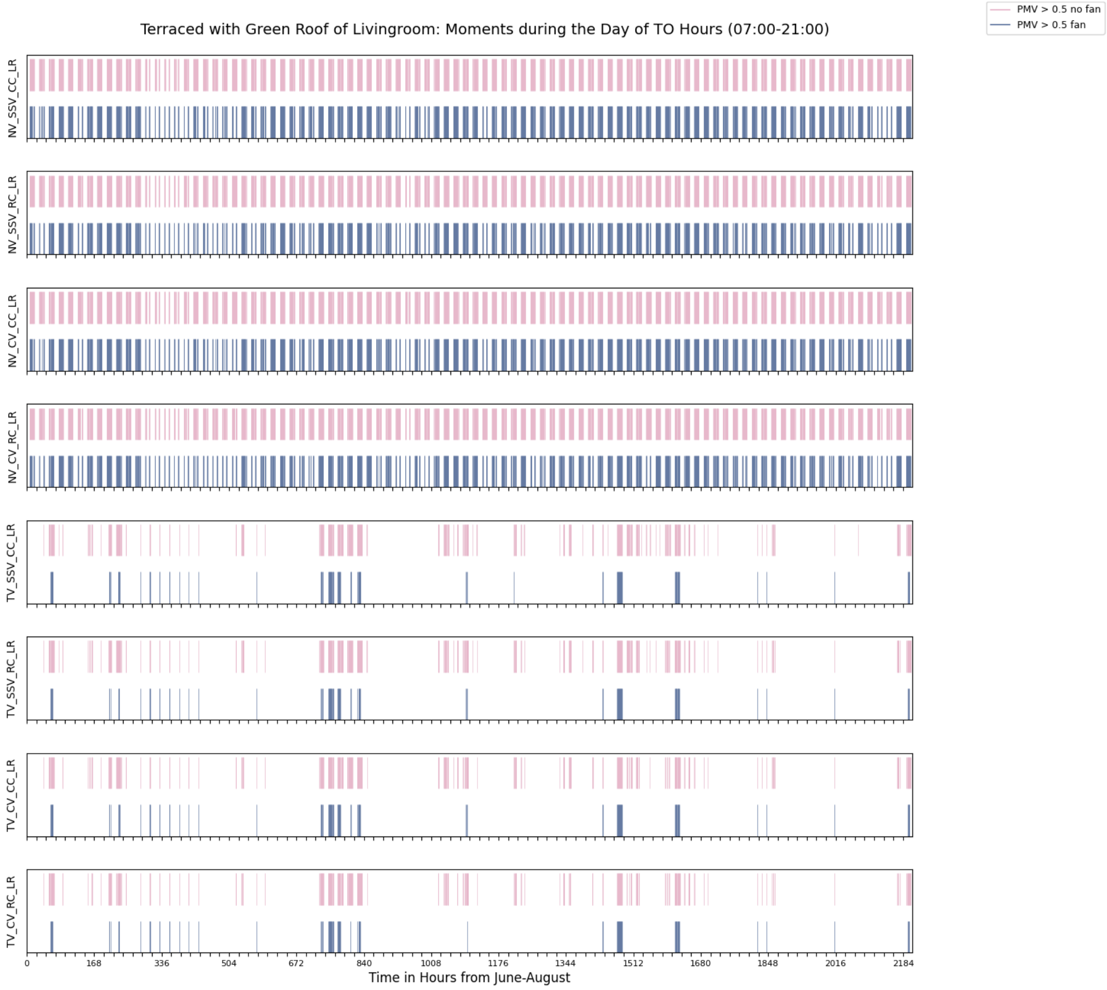


5.23.2



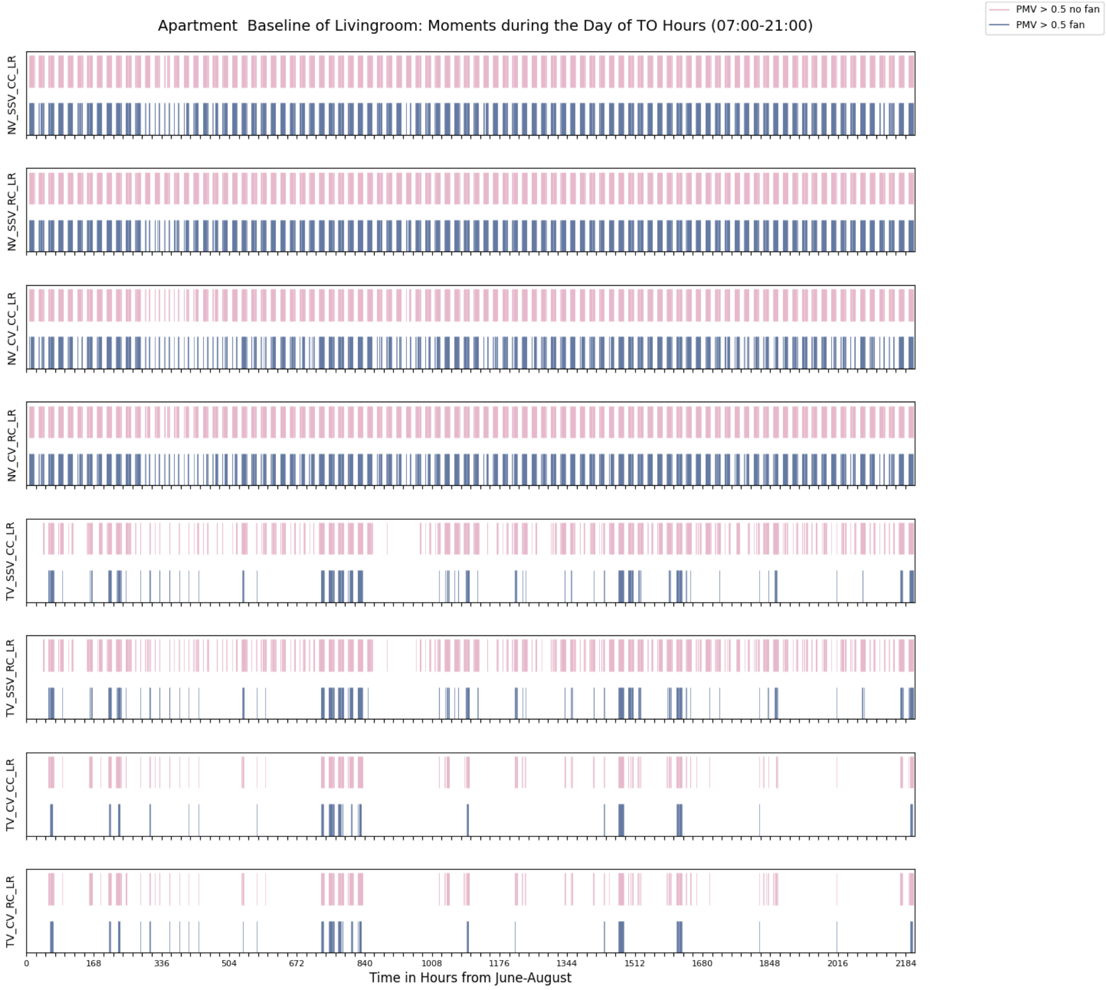
5.23 Hourly Exceedance of PMV>0.5 in the Livingroom - Terraced

5.23.3

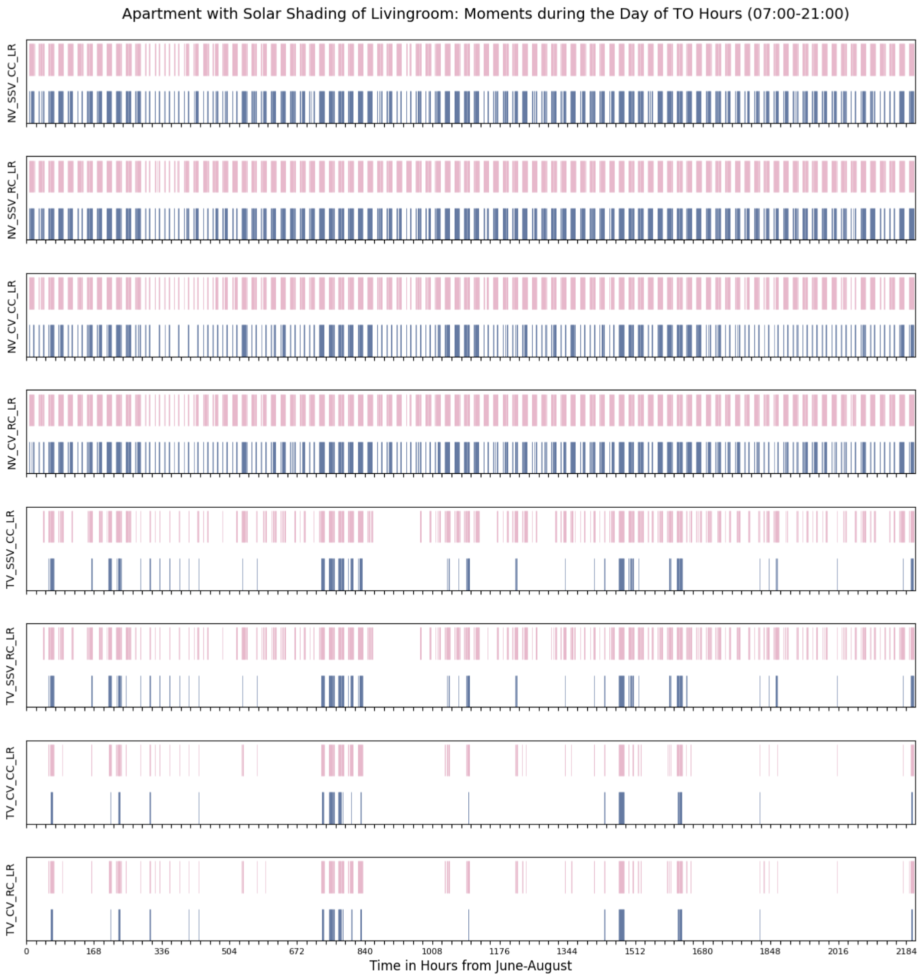


5.24 Hourly Exceedance of PMV>0.5 in the Livingroom - Apartment

5.24.1

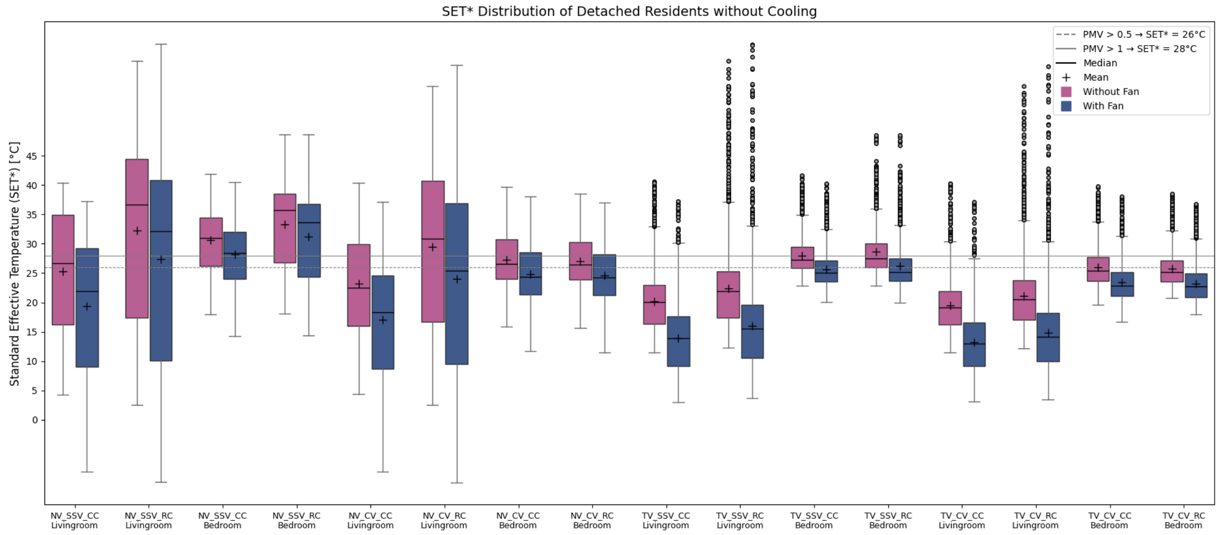


5.24.2

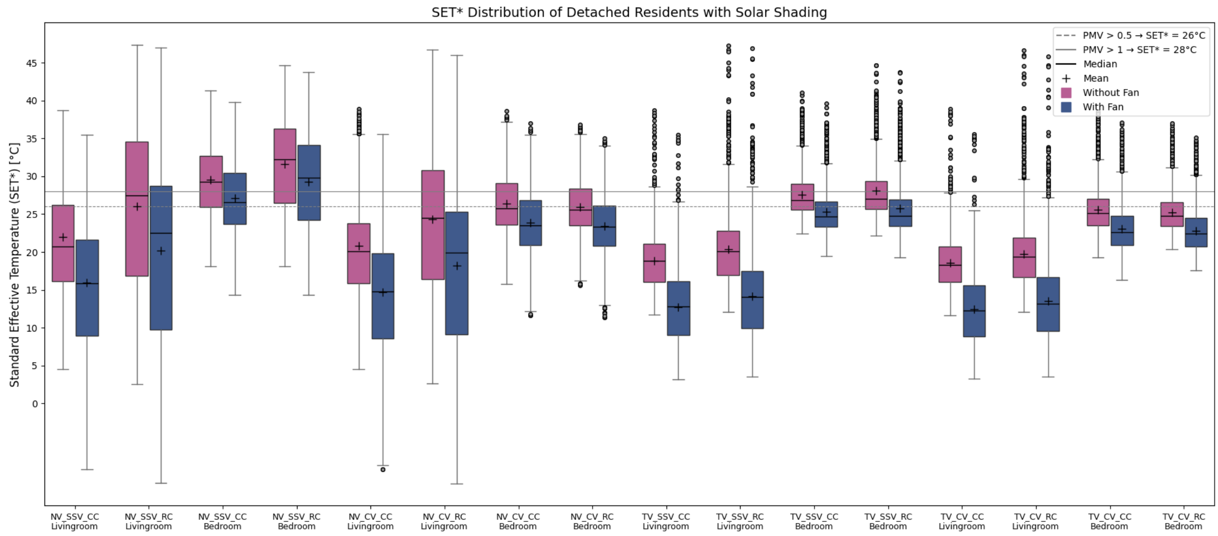


5.25 SET* Distribution - Detached

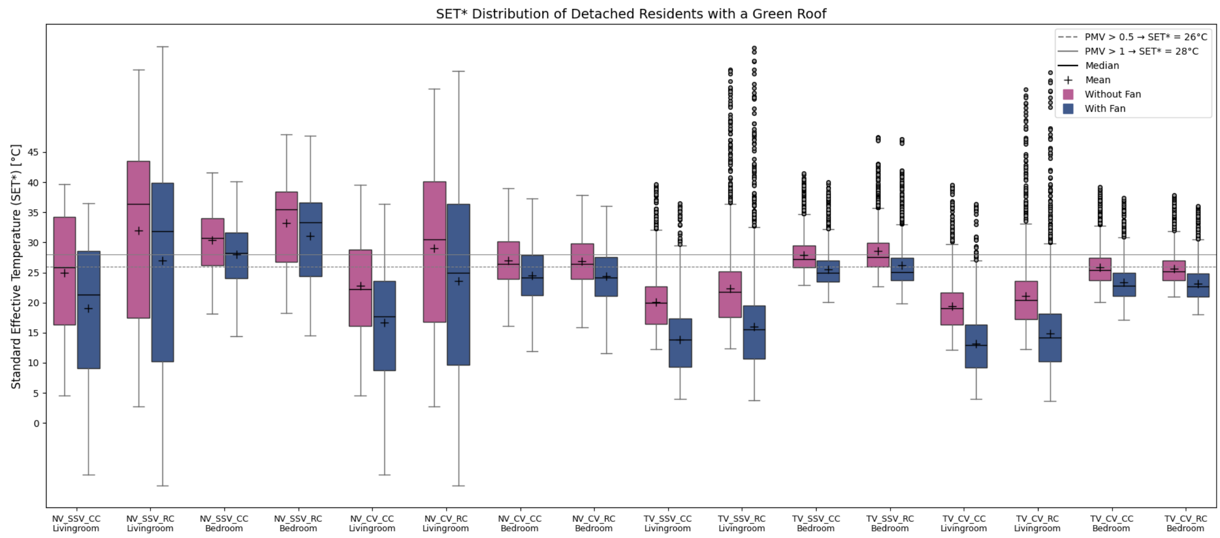
5.25.1



5.25.2

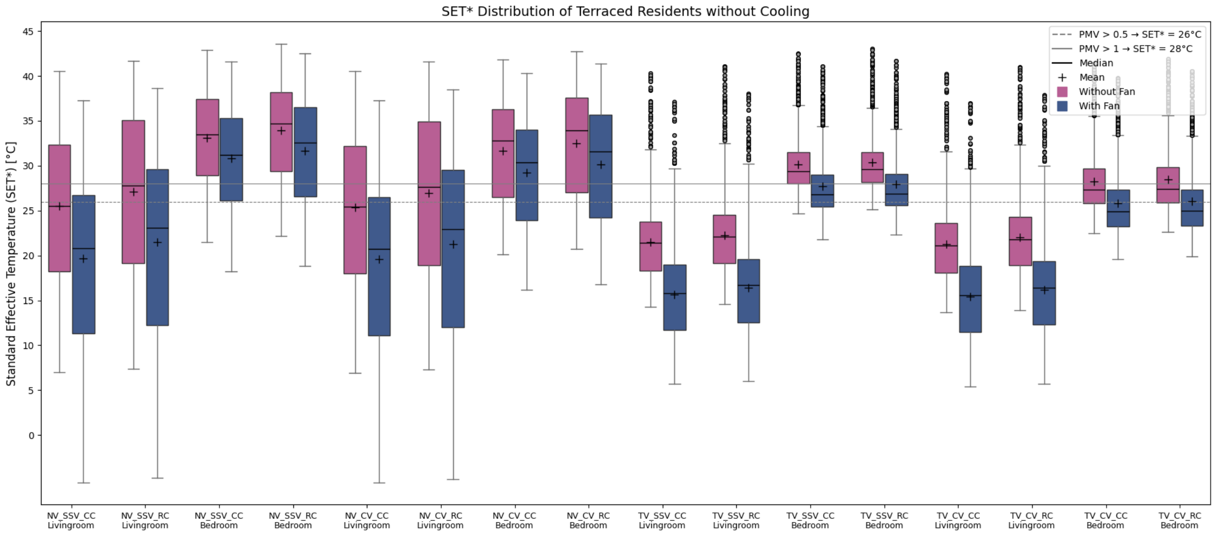


5.25.3

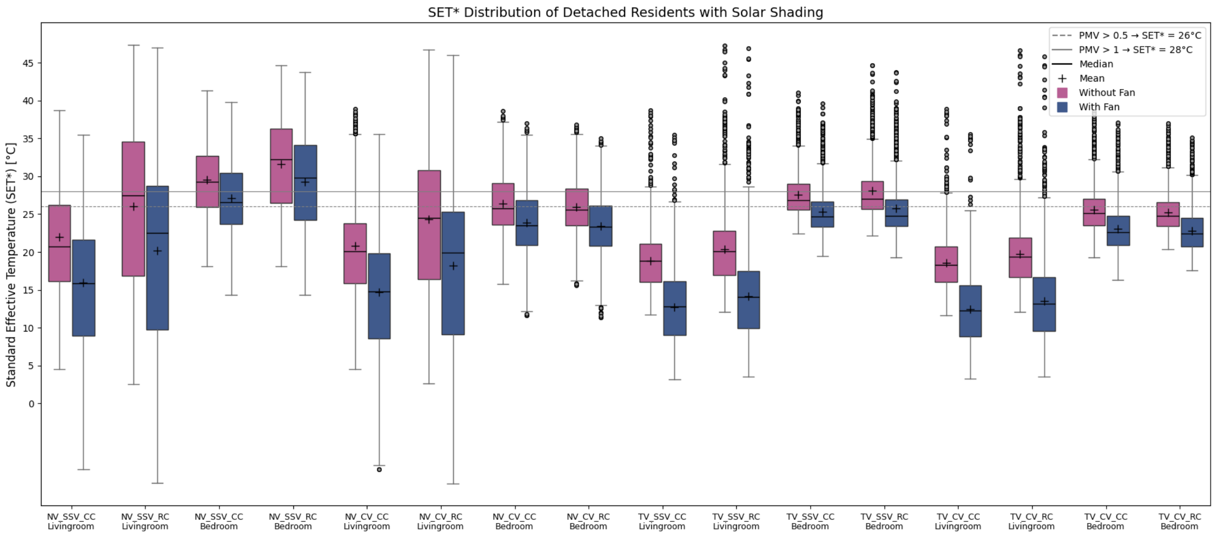


5.26 SET* Distribution - Terraced

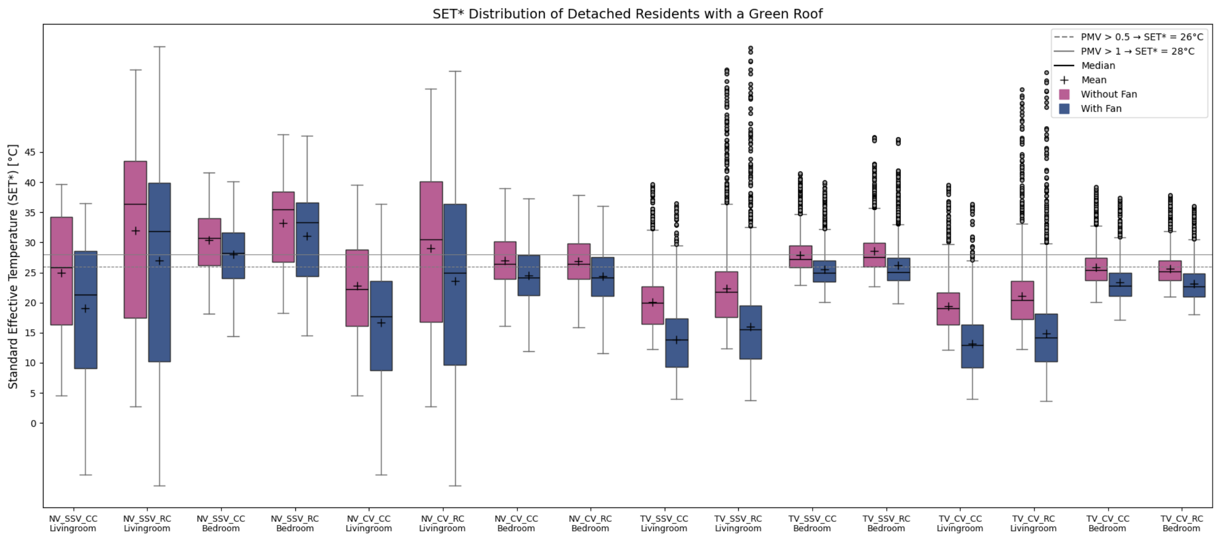
5.26.1



5.26.2

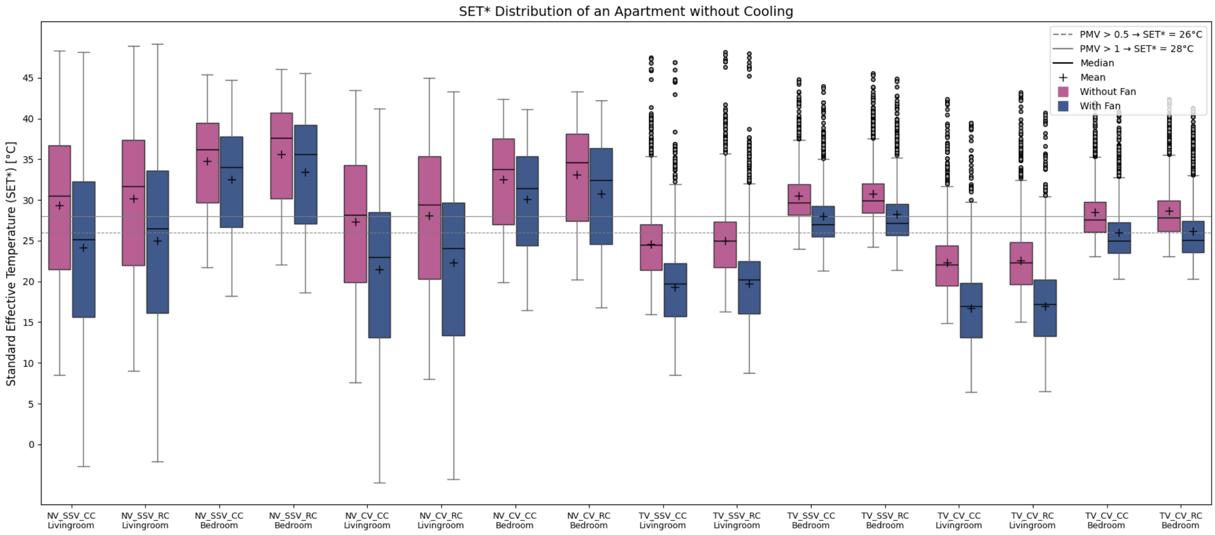


5.26.3



5.27 SET* Distribution - Apartment

5.27.1



5.27.2