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Overheating Risk Assessment in Insulation-Based Energy Renovations in Spain

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Abstract **– This study examines the impact of thermal insulation-based renovations on the overheating risk in residential buildings across different climatic conditions in Spain. While the European Union (EU) regulations aim to improve energy efficiency in buildings, increasing thermal insulation can lead to significant energy savings, especially in areas with high heating demand. However, excessive insulation may raise indoor temperatures, increasing the risk of overheating. The research focuses on a typical multi-family residential building from the 1960s and 1970s, initially lacking insulation, and analyses various renovation strategies in different climatic conditions in Spain. The study evaluates four types of passive renovations—facade exterior insulation, roof insulation, window replacement, and their combination – at three efficiency levels – basic, national building code (NBC) required, and EnerPHit standard. A three-stage methodology is employed: identifying archetypes and renovation strategies, conducting a Building Performance Simulation (BPS), and assessing overheating hours based on the CIBSE thermal comfort model. Results reveal that climatic conditions significantly influence overheating risks, identifying critical zones in Spain where overheating may be a concern. The findings suggest that these areas require more targeted solutions to prevent overheating while improving energy efficiency through renovations.**

Keywords **– BPS (Building Performance Simulation); climate; energy renovation; EnerPHit; National Building Code (NBC); thermal comfort; thermal insulation.**

1. Introduction

1.1. Context

The push for energy efficiency in buildings has become a critical aspect of European Union (EU) policies, aiming to reduce greenhouse gas emissions and mitigate climate change [1]. The latest updates of the Energy Performance Building Directive (EPBD) – Directive 2018/844 [2] and Directive 2024/1275 [3], as well as the Recommendation 2019/786 [4], aim the reduction of energy consumption and global warming potential of existing buildings. Therefore, energy renovation strategies are among the most promising actions, as around 75 % of the existing buildings are considered inefficient [1]. For this, renovation strategies based on the increase of thermal insulation of the envelope are one of the most applied strategies for reducing energy demand [4], which is the most applied strategy in heating dominant climates [5]. Moreover, insulation-based strategies constitute a fundamental

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element in enhancing the energy efficiency of buildings [6], [7] and are essential for achieving optimal levels of thermal performance [8].

National regulations, such as the National Building Code (NBC) of Spain "Código Técnico de la Edificación" (CTE) [9], have progressively incorporated stricter energy efficiency requirements, largely emphasizing thermal insulation as a means to reduce heating demand in residential buildings. The 2019 revision of the "Energy saving" document of the NBC – "CTE DB-HE" – has further increased requirements related to thermal insulation, airtightness, and primary energy consumption limits, aligning with the EU's nearly Zero Energy Building (nZEB) targets [9].

Going beyond mandatory regulations, the adoption of voluntary certification standards, such as Passivhaus [10] and EnerPHit [11], has reinforced the use of high-performance thermal envelopes in both new construction and renovations. These approaches prioritize superinsulation, airtight detailing, and mechanical ventilation with heat recovery [10], [11].

However, highly insulated and airtight buildings are known to have overheating problems. Some studies that conducted monitoring campaigns in Passivhaus dwelling in the UK [12], [13] found a clear high overheating risk. Another study [14], this time including monitoring and surveys, confirmed severe overheating issues in a Passivhaus-certified residential building in Spain. These studies demonstrate that the overheating risk need to be analysed in highly insulated buildings, including renovation projects. Moreover, the latest update of the EPBD – Directive 2024/1275 [3] – mentions that there should be a particular emphasis on implementing measures that prevent overheating. More precisely, other studies have investigated geographically urban-scale indoor overheating vulnerability [15]. Furthermore, energy renovations focused on reducing the heating energy demand can aggravate the indoor environment [16], [17].

The relationship between high temperatures and health issues is deeply studied. For instance, some studies have shown the increase in mortality caused by extern summer hot conditions, occurred in the heat waves of 2003 and 2006 in Europe [18], [19]. Therefore, while retrofit strategies have the potential to reduce carbon emissions by enhancing building energy efficiency, they may also result in unintended consequences, such as the reduced capacity to mitigate the heat during the night in summer periods, causing overheating, and consequently, occupants' health conditions [20].

Overheating risks are exacerbated by Spain's diverse climate. The country spans multiple climatic zones, ranging from cooler northern coastal areas (e.g., Basque Country, Asturias, and Galicia) to the warm Mediterranean and continental inland regions (e.g., Madrid, Seville, and Valencia). While insulation-based strategies are highly effective in cold and mixed climates, their impact in warm or temperate regions is more complex [21]. For instance, studies in the Basque Country demonstrated that newer, highly insulated buildings can experience higher indoor temperatures than older, less insulated dwellings, particularly when ventilation is limited [22]. Other studies have focused on measuring the overheating of urban areas using geographical information systems [23] confirming the existence of vulnerable areas in cities like Seville. Moreover, studies monitoring real-life nZEB buildings in Northern Spain have confirmed that overheating is a recurring issue, especially in summer and mid-season periods, where solar gains and internal heat loads are not effectively dissipated [14].

Consequently, heat-related health issues have raised concern in European countries like Spain, where the government published the National Plan of Preventive Actions on the Effects of Excessive Temperatures on Health in 2004 and updated in 2022 [24]. However, there are no mandatory regulations to prevent excess heat in indoor environment and the NBC does not include any specific measure to limit overheating risk [9].

1.2. Objective

Given these challenges, it is essential to assess the overheating risks associated with insulation-based renovations across different climatic conditions in Spain. However, there is a lack of studies focused on specifically evaluating the influence of insulation-based renovation on overheating of residential buildings in the heterogeneous climatic conditions of Spain. Therefore, the objective of the study is to overheating risk of residential environments caused by insulation-based renovations, with a specific focus on the varying climatic conditions across Spain. The study analyses how various renovation strategies – including façade insulation, roof insulation, and window replacement – affect indoor thermal comfort under different efficiency levels (basic, NBC-compliant, and EnerPHit-certified). Using Building Energy Modelling (BEM), Building Performance Simulation (BPS) and overheating assessment criteria of CIBSE Guide A [25], this research aims to identify the climatic zones most vulnerable to overheating.

2. Methodology

To achieve this, the study examines the thermal performance under various renovation scenarios applied to a typical multi-family residential archetype from the 1960s and 1970s, originally without thermal insulation, applying a three-stage methodology. First, the study defines the case study and the evaluation scope. Second, the study models and simulates, by BEM and BPS employing Energy-Plus, the scenarios to be evaluated focusing on the hourly temperature data. Third, the study evaluates the overheating risk of baseline and renovated scenarios by analysing the indoor thermal comfort based on CIBSE "Guide A" [25].

2.1. Definition of the Case Study and Evaluation Scope

The first stage defines the case study: a series of residential scenarios composed of three components: archetype, climatic conditions and renovation strategies.

Firstly, the study selects one reference archetype for the evaluation: a typical multifamily residential building of the 1960s and 1970s of Spain, with four storeys and eight dwellings (see Fig. 1). The construction date of the archetype is before the first energy efficiency regulation of Spain, the "NBE-CT-79" [26], set on 1979, which means that the archetype has no insulation in the opaque thermal envelope and the windows have a high thermal transmittance and low airtightness (with an air change of 9 h^{-1} based on an empirical study [27]). The building is equipped with a heating system with water radiators using individual gas boilers and does not have a cooling system. The investigation only considered one orientation of the building due to the double orientation of the dwellings [28].

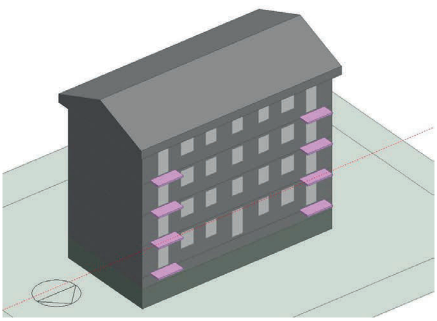

Fig. 1. Model visual representation by Design-Builder.

Secondly, we analyse 50 climatic conditions, one per province of Spain, using the climatic data from the capitals of each province from the period of 2009–2023.

Thirdly, the study selects 12 renovation strategies composed of four types of insulation-based interventions— façade insulation, roof insulation, window replacement and complete renovation – and three levels of renovation – basic level, NBC level and EnerPHit standard level. Regarding the renovation strategies, the first strategy consists of the façade exterior thermal insulation composite system (ETICS). The second strategy is the insulation of the roof adding a new covering, and assembling the insulation bellow the tiles. The third strategy is the replacement of the original windows by more efficient ones with lower thermal transmittance and higher airtightness. The fourth strategy is the complete renovation combining the previous three interventions – façade insulation, roof insulation and window replacement. On the other hand, each renovation level defines the insulation requirements according to different climatic zones. The first level is the basic renovation, and it accomplishes half of the thermal insulation required by the NBC, considering climatic zones defined in the section "DB-HE" about energy saving [9]. The second renovation degree is aligned with the NBC required insulation level. The third renovation level is the EnerPHit standard, adjusting the thermal transmittance of each intervention to the requirements of the EnerPHit certificate [11]. The combination of the four types of intervention and three levels composes the 12 renovation strategies shown in Table 1, indicating the insulation thicknesses (for façade, roof, or both) considering a thermal conductivity of 0.04 W/m·K, window frame U-values and glass U-values by climatic zones. The parametric combination of the three components – 1 archetype, 50 climatic conditions and 12 renovation strategies – complete 600 renovation scenarios and 50 baseline scenarios.

TABLE 1. DEFINITION OF RENOVATION STRATEGIES

Renovation		**Insulation Thickness, cm**					**Window frame U, $W/m^2·K$**					**Window Glass U, $W/m^2·K$**				
		A	**B**	**C**	**D**	**E**	**A**	**B**	**C**	**D**	**E**	**A**	**B**	**C**	**D**	**E**
F1	Façade – Basic	2	2.5	3	4	5	–	–	–	–	–	–	–	–	–	–
F2	Façade – NBC	4	5	6	8	10	–	–	–	–	–	–	–	–	–	–
F3	Façade – EnerPHit	6	6	12	12	12	–	–	–	–	–	–	–	–	–	–
R1	Roof – Basic	4	4	5	6	6	–	–	–	–	–	–	–	–	–	–
R2	Roof – NBC	8	8	10	12	12	–	–	–	–	–	–	–	–	–	–
R3	Roof – EnerPHit	8	8	14	14	14	–	–	–	–	–	–	–	–	–	–
W1	Windows – Basic	–	–	–	–	–	1.4	1.4	1.1	1.1	1.1	2.1	2.1	1.5	1.5	1.5
W2	Window – NBC	–	–	–	–	–	1.4	1.4	1.1	1.1	1.1	2.1	2.1	1.5	1.5	1.5
W3	Window – EnerPHit	–	–	–	–	–	1.1	1.1	1.1	1.1	1.1	1.2	1.2	1.2	1.2	1.2
C1	Complete – Basic	2/4	2.5/4	3/5	4/6	5/6	1.4	1.4	1.1	1.1	1.1	2.1	2.1	1.5	1.5	1.5
C2	Complete – NBC	4/8	5/8	6/10	8/12	10/12	1.4	1.4	1.1	1.1	1.1	2.1	2.1	1.5	1.5	1.5
C3	Complete – EnerPHit	6/8	6/8	12/14	12/14	12/14	1.1	1.1	1.1	1.1	1.1	1.2	1.2	1.2	1.2	1.2

2.2. Modelling and Simulation

The BEM and BPS of all the scenarios are carried out in the environment of Energy-Plus. For this, we use Enegy-Pus weather (EPW) files for the climatic conditions and Intermediate Data Format (IDF) files for the model of the archetype.

On the one hand, the EPW climate files are obtained from the International Weather for Energy Calculation database [29], using the climatic file from the capital of each province.

On the other hand, we modelled the archetype using Design-Builder [30] and then exported as an IDF file. All the scenarios are modelled following the parameters shown in Table 2, defined by the NBC. Additionally, the study considers night ventilation for summer (from June to September, from 00:00 to 08:00) with an airflow of 3.00 ach of natural ventilation (data from the NBC [9]). Besides, no solar shading is incorporated, apart from the protection of the exterior reveal of 15 cm. The modelling of renovation strategies is done by modifying the baseline IDF model using the Eppy scripting language [31] due to the possibility of programming and automatizing the process. Therefore, with the EPW files and IDF baseline models, employing a script written in Python 3, we modelled and simulated all the scenarios, performing an hourly BPS in the period of one year for each of the 650 scenarios. The simulation took around three hours on an eight-core computer.

TABLE 2. MODELLING PARAMETERS

Occupancy	Occupancy schedule	Nat. Ventilation	Lighting gains	Internal gains
0.03 people/m^2	0–6h: 1.00; 7–14h: 0.35; 15–23h: 0.95	0.63 ach	3.40 W/m^2	4.40 W/m^2

2.3. Overheating Risk Assessment

As a result, we got the hourly indoor operative temperature of the western dwelling of one intermediate level of each scenario. Then, we study process and analyse all the data calculating the total overheating based on the comfort model by CIBSE Guide A [25]. For this, we measure the overheating of each scenario by calculating the total overheating hours during the year under two conditions and thresholds (see Table 3): the comfort condition for the living room, considering the 24 hours of the day, and with the maximum comfort temperature of 28 °C; and the comfort condition for the bedroom, considering only the night hours (from 22:00 to 7:00), and the maximum comfort temperature of 26 °C.

TABLE 3. COMFORT MODEL BASED ON CIBSE GUIDE A

Comfort condition	Hours	Temperature threshold
Living room	24 hours	28 °C
Bedroom	22:00–07:00	26 °C

For this assessment, firstly, we calculate the total hours of overheating during the year of each baseline and renovated scenarios classified by the climatic zones defined by the NBC, for both living room and bedroom conditions. Each climatic zone is determined by the climatic data from the biggest city of each climatic zone, e.g. for the climatic zone "C1" we considered the simulations performed with the climatic data from Bilbao. This indicator can determine the degree of overheating of each climatic zone in the baseline and renovated scenarios, enabling the comparison between the different climatic conditions. Secondly, we calculated the overheating increase caused by the renovation strategies, in hours during the year, classified by the different renovation strategies and climatic zones defined by the NBC. As the previous analysis, this one also applies both comfort conditions for the living room and bedroom. This second indicator measures the effect of different renovation strategies in different climatic conditions, revealing how different types of renovation strategies and renovation levels can increase or reduce the overheating hours in each climatic zone. Thirdly, we evaluate the overheating vulnerability of different climatic conditions across Spain, including the geographical analysis of all the provinces. For this, we develop the indicator "overheating risk factor" (ORF), which includes the existing baseline overheating degree and the overheating increase caused by the complete renovation strategy at the NBC level. This indicator is created for both overheating conditions for living rooms and bedrooms, and it is defined by Eq. (1).

$$ORF_i = \frac{BO_i}{BO_{\max}} \cdot 0.5 + \frac{OI_i}{OI_{\max}} \cdot 0.5, \quad (1)$$

where

BO_i baseline overheating of the scenario *i*, h;

$BO_{\max}$ maximum baseline overheating, h;

OI_i overheating increase of the scenario *i*, h;

$OI_{\max}$ maximum overheating increase, h.

3. RESULTS

3.1. Overheating at Baseline and Renovated Scenarios by Climatic Zones

Fig. 2 illustrates the total annual overheating time and the corresponding percentage of hours, for both the baseline and renovated scenarios, for both living room conditions and bedroom conditions.

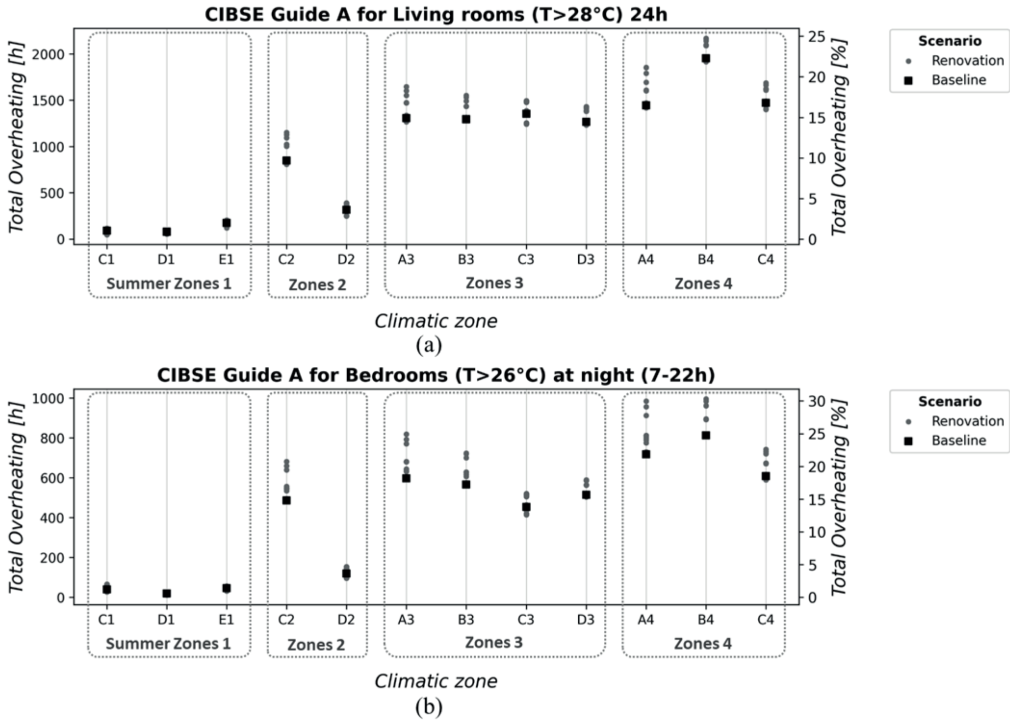

Fig. 2. Total overheating of baseline and renovation scenarios for living rooms ($T > 28$ °C) during the 24 h and for bedrooms ($T > 26$ °C) during the night from 22:00 to 7:00, by climatic zones (being summer zones 1 the coldest summer condition zones, and summer zones 4 the warmest ones).

The results highlight the substantial influence of the summer climatic zone, defined by the numerical digit of each climate zone identifier, from “1” (representing the coldest summer conditions) to “4” (indicating the mildest conditions). In the first summer zone, overheating remains relatively limited in comparison to zones “3” and “4”, where most scenarios exceed 15 % of hours in overheating for both the living room and bedroom conditions.

About the renovation scenarios, in the first summer zones, overheating does not exhibit any significant increase or decrease. However, in most of the remaining climatic zones, overheating tends to increase more substantially. This suggests that, based on this initial analysis, insulation-based renovations may exacerbate overheating, particularly in cooler climatic zones. Besides, a correlation is observed between the extent of overheating in the baseline scenario and the increase in overheating following renovation.

Regarding living room and bedroom conditions, the percentage of overheating is higher in the bedroom condition, and thus, during nighttime hours. Adding insulation in the thermal envelope may reduce heat dissipation at night, leading to an increase in overheating hours. This phenomenon poses a potential risk to thermal comfort during the night, which may have a more pronounced impact on sleep quality and occupant well-being than a reduction in comfort during daytime hours.

3.2. Overheating Increase Caused by Renovation by Climatic Zones

The initial analysis indicates a predominant trend whereby renovation strategies contribute to an increase in household overheating. However, the extent of this increase varies depending on climatic conditions, the type of renovation strategy, and the renovation level.

Focusing on specific climatic zones, a clear contrast emerges between zone “A4” (Fig. 3(a) and Fig. 4(a)), representing the warm summer conditions with 214 heating degree days (HDD) and 337 cooling degree days (CDD) (calculated with base temperatures of 15.5 and 24 °C); and zone “C1” as seen in Fig. 3(b) and Fig. 4(b) with 739 HDD and 60 CDD, representing the cold summer conditions. The impact of renovation strategies differs significantly between these zones, with overheating effects being more pronounced in the cooler climatic zone. In zone “A4”, overheating increases by more than 400 hours per year, of which over 250 hours occur during the night. This trend is consistently observed across other climatic zones, underscoring the importance of considering the potential for increased overheating in cooler climatic zones of Spain (summer zones 2, 3, and 4).

Regarding renovation strategies, combined renovation approaches result in the highest overheating increases in cool summer zones. Conversely, in colder summer zones, combined strategies have a less pronounced effect, as demonstrated in zones “A4” and “C1” (Figs. 3&4). Among single intervention strategies, window replacement emerges as the most influential factor in increasing overheating. This effect is attributed not only to the lower thermal transmittance of the building envelope but also to the lower emissivity and higher airtightness of new generation windows. Across all climatic zones analysed, window replacement consistently leads to increased overheating, identifying it as the most impactful strategy in this regard. On the other hand, façade insulation is the only intervention that can mitigate overheating. However, its impact varies by climatic zone and comfort condition. In some cases, while it improves comfort in living room conditions, it may exacerbate overheating during nighttime hours, as observed in zone “A4”, Fig. 3(a) and Fig. 4(a).

The level of renovation also plays a crucial role. In most scenarios, the renovation level does not alter the overall trend of each strategy—whether it increases or decreases overheating. For example, in zone “A4”, the increase in overheating associated with the combination strategy for living room conditions aligns with the renovation level, see Fig. 3(a), whereby higher renovation levels correspond to a greater overheating risk. However, in certain cases, this trend may be reversed. For instance, in zone “A4”, façade renovation for living rooms initially leads to a reduction in overheating at the “light” renovation level, yet at more advanced renovation levels the effect becomes positive, resulting in an overheating increase as depicted in Fig. 3(a).

These results derived from BEM are aligned with previous study based on monitored data [22], which conducted a comparative analysis of the summer comfort in three different dwellings in norther Spain, built under different energy efficiency regulations. The most advanced energy efficient case study, a Passivhaus certified building from 2018 with a U-value of the façade of 0.22 W/m²·K, reported 906 hours above 25 °C in July and August. The medium level case study, built in 2006 under the energy efficiency "NBE-CT-79" [26] with a U-value of the façade of 0.52 W/m²·K, reported 855 hours above 25 °C in the same period. And the third case study, a residential building from 1900 without energy efficiency measures with a U-value of the façade between 1.70–2.0 W/m²·K, reported 405 hours above 25 °C. Therefore, even if this study can be limited, it shoes the trend the higher is the energy efficiency related with the thermal insulation, the higher is the overheating level.

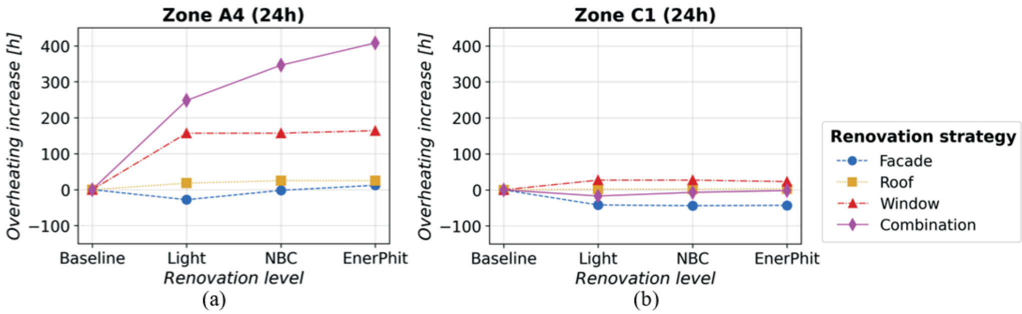

Fig. 3. Overheating increase (hours per year) caused by renovations for Living rooms ($T > 28$ °C) during the 24 h in climatic zones A4 (a) and C1 (b).

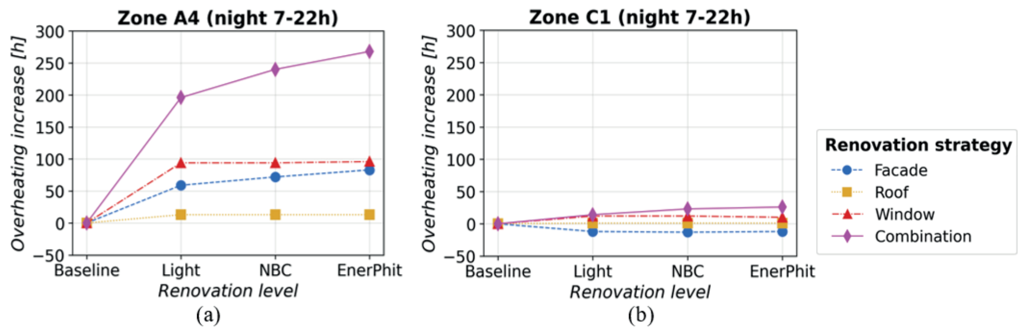

Fig. 4. Overheating increase (hours per year) caused by renovations for Bedrooms ($T > 26$ °C) during the night from 22:00 to 7:00 in climatic zones A4 (a) and C1 (b).

3.3. Overheating Vulnerability by Geographical Areas

According to the NBC, all renovations of existing buildings must comply with the requirements of energy demand limitation outlined in the document "DB-HE-1" [9]. Consequently, the "combination" renovation strategy at the NBC level adheres to these requirements, which are tailored to each climatic zone. This section examines the overheating risk across the geographical zones of Spain (by province) in relation to the implementation of the combination renovation strategy that fulfils NBC regulations.

On the one hand, the baseline scenario reflects the degree of overheating in each province, with some scenarios showing nearly 25 % of overheating hours for bedroom conditions during the night, while others exhibit less than 5 %, as shown in Fig 5(a). It is important to note that, although a 5 % overheating level may appear low in comparison to high-overheating scenarios, the CIBSE Guide A [25] defines overheating as commencing at just 1 % of time exceeding the threshold. This indicator is critical, not only because overheating is already present in the baseline scenario, but also because scenarios with high baseline overheating levels are more susceptible to further overheating increases following insulation-based renovations. As illustrated in Fig. 5(a), the initial factor contributing to the risk of overheating is the existing overheating levels in baseline situation.

Annex 1 and Annex 2 present graphical results for all climatic zones, illustrating overheating trends in living room conditions and bedroom comfort conditions, respectively.

On the other hand, the overheating increase resulting from the application of the "combination" renovation strategy at the NBC level demonstrates how the insulation requirements mandated by the NBC can contribute to overheating (see Fig. 5(b)). This metric represents the second component of the overheating risk assessment. The results indicate a positive trend in overheating increase across all regions, highlighting the negative impact of these mandatory requirements on overheating risk. Specifically, under bedroom comfort conditions during the night, the percentage of overheating hours can increase by five percentage points, reaching levels exceeding 30 % of overheating hours. By integrating these two components – baseline overheating and overheating increase due to renovation – this study develops the "overheating vulnerability factor". This factor focuses on bedroom comfort conditions, which are considered the most critical for occupant rest and well-being.

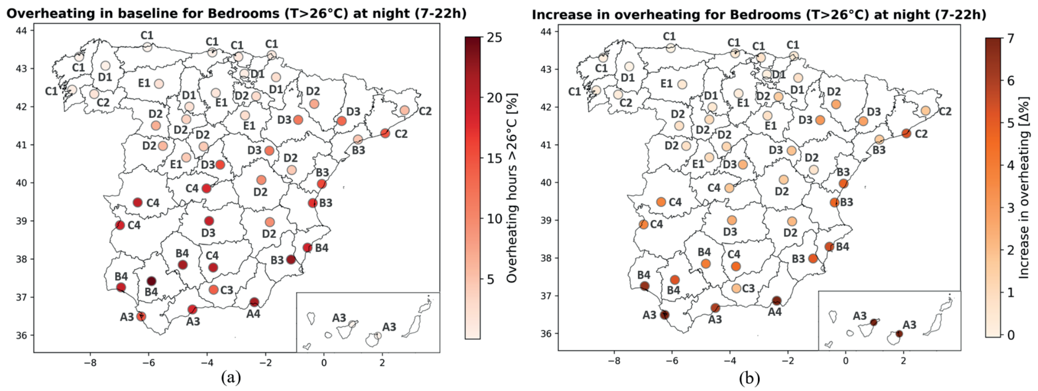

Fig. 5. Geographical distribution of the total overheating in baseline scenario in percentages (a) and overheating increase in the scenario of complete renovation at NBC level in percentage increase (b) for Bedrooms ($T > 26$ °C) during the night.

Fig. 6 presents the results of the overheating risk assessment using this factor for all Spanish provinces, ranging from a minimum risk factor (0.00) to a maximum risk factor (1.00). It is essential to emphasise that this factor is comparative: a low factor does not imply an absence of overheating risk but rather indicates that the overheating risk is lower relative to other regions. The analysis of the two components, alongside the final vulnerability assessment, reveals a clear pattern: the highest overheating vulnerability is concentrated in south-eastern areas, whereas north-western areas exhibit lower risk levels.

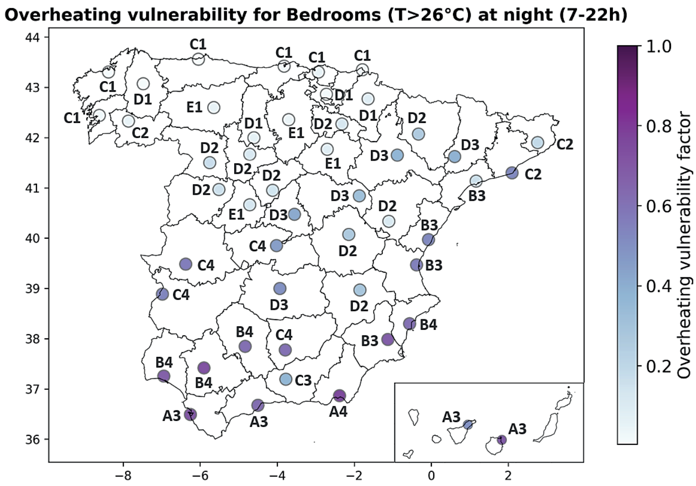

Fig. 6. Geographical distribution of the 'Overheating vulnerability factor' considering the scenario of complete renovation at NBC level for the comfort condition for Bedrooms ($T > 26$ °C) during the night.

4. DISCUSSION

The results indicate that overheating is present in all scenarios analysed, with more than 1 % of annual hours exceeding the established comfort thresholds, according to the comfort model by CIBSE Guide A [25]. In most of the scenarios, this issue is worsened when applying thermal insulation-based renovation strategies. The most critical condition is found during night hours, with higher overheating percentages and an increase in renovated scenarios, where high insulation levels restrict heat dissipation, significantly affecting occupant comfort in sleeping hours. This suggests that could lead to well-being concerns, especially in warmer climatic zones where heat accumulation is more pronounced. Therefore, including the evaluation of comfort during sleeping hours provides an extra novelty, which although other studies mention it, does not assess it in particular [17], [32].

Among the different renovation strategies analysed, façade insulation was the only intervention with potential benefits for reducing overheating in certain cases. However, its effectiveness varies depending on the climatic context and other factors. Moreover, while it has been observed to improve thermal comfort in certain scenarios considering the 24 hours of the day, its impact on bedroom conditions during the night is less clear. In some climatic conditions, façade insulation can contribute to increase overheating under bedroom conditions (during the night), even if the overheating according to living room conditions (during the 24 hours) can be decreased. On the other hand, window replacement showed the impact on overheating increase due to the low emissivity and higher airtightness of new generation windows. This suggests that while window replacement is an effective strategy for reducing heat losses in winter, it poses a significant risk of overheating in summer unless combined with adaptive measures, such as shading or ventilation strategies [33].

Overall, the findings indicate that higher thermal insulation levels consistently lead to increased overheating, especially in bedroom conditions at night. While insulation is crucial for energy efficiency and winter comfort, excessive insulation without proper overheating mitigation strategies can compromise occupant well-being. This is particularly relevant given the NBC of Spain requirements, which emphasize high insulation levels without explicitly addressing overheating risks [9]. Similarly, high-performance energy certifications, such as EnerPHit [11], encourage extreme insulation standards that may inadvertently contribute to overheating problems. It is therefore critical that all insulation-based renovation projects undergo a comprehensive overheating risk assessment.

Given that climatic zones with higher baseline overheating levels tend to experience greater overheating increases after renovations, specific mitigation strategies should be incorporated when energy efficiency improvements are implemented. Solar protection interventions, including external shading devices, and optimized ventilation strategies, can lower the risk of overheating [33], [34]. In this regard, future research work will focus on the analysis of overheating mitigation strategies for the different climatic conditions of Spain.

Besides, this study faces various limitations. On the one hand, the accuracy of the energy model can vary depending on each single case study. A previous study [35] showed that the limited accuracy of BEM in collective residential buildings. However, the purpose of this study is to provide the general trends of a generic model. Thus, the case study is based on normative parameters. On the other hand, the scenarios of the case study are limited with one archetype, one occupant behaviour model and present climatic model. Future works will focus on analysing diverse case studies with multiple archetypes, occupant behaviour models (especially regarding ventilation, internal gains and occupancy related parameters) and future climatic models, such as "representative concentration pathway" (RCP) scenarios.

These findings underscore the importance of adopting a more tailored approach to energy renovations, considering the distinct overheating risks associated with different climatic conditions in Spain. Future policies and building codes should not only focus on reducing heating demand but also incorporate mandatory overheating assessments to ensure that energy efficiency measures do not compromise the well-being of occupants. These new measures could require a mandatory overheating assessment for every intervention that could potentially increase the overheating risk, including the definition of temperature thresholds and a maximum number of hours above these limits. Furthermore, we also believe that heating energy demand restrictions should be revised for certain climatic zones were a high insulation envelope than increase overheating risk, considering also the future climatic scenarios.

5. Conclusion

This study highlights the significant impact of insulation-based energy renovations on overheating risk in residential buildings across different climatic conditions in Spain. The findings indicate that while increasing insulation effectively reduces heating demand, it also leads to higher indoor temperatures. Overheating was observed in all scenarios, with the most critical impact occurring during night hours, where heat retention is exacerbated. Among the renovation strategies analysed, window replacement contributed the most to overheating, as low-emissivity glazing and higher airtightness reduces passive cooling. In contrast, façade insulation showed some potential to mitigate overheating in living rooms, though its effectiveness varied depending on climate and building conditions.

The study underscores the need for overheating risk assessments in energy renovation projects, especially in warm and temperate climates. The NBC of Spain should incorporate overheating assessment procedures and mitigation strategies, such as solar shading, controlled ventilation, and reflective materials, to balance energy efficiency with occupant comfort. Future policies should ensure that insulation improvements do not compromise indoor thermal comfort, particularly in high-performance buildings. By integrating adaptive cooling strategies into energy renovations, Spain can transition toward a more sustainable and resilient built environment while safeguarding the well-being of its residents.

ANNEX

Zenodo: https://zenodo.org/records/16892469

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