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Facing Climate Change in a Temperate European City: Urban-Scale Diagnosis of Indoor Overheating and Adaptation Strategies for Residential Buildings

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Abstract: The rise in outdoor temperatures and heatwaves highlights the limitations of buildings in adapting to warming conditions, even in temperate climates. This paper analyses the indoor overheating of residential dwellings in Pamplona (a city in northern Spain, with a Cfb climate) using an urban-scale diagnostic methodology and presents different envelopes' retrofitting scenarios as a strategy to reduce it. The results come from energy simulations conducted during an extremely warm summer in 2022, considering the microclimate effects. The residential typologies most vulnerable to overheating are those with only one orientation, built before the EPBD 2002, and located on top floors. These dwellings show a 23.7% mean of indoor overheating hours (IOH), representing approximately 870 h above the EN 16798-1:2019 adaptive threshold from May to September. Renovating building envelopes to meet current energy standards reduces the IOH by an average of 8.6% and up to 15.35% in the most vulnerable typologies. In the retrofitting scenario with green roof systems, indoor temperatures are up to 0.5 °C lower than when roofs are renovated with traditional systems. This study assists policy-makers in preventing the risk of overheating within cities and encourages them to promote nature-based solutions in order to adapt urban residential buildings and cities to warming conditions.

Keywords: building parameters; natural cooling; green roofs; traditional roofs; thermal envelopes; heatwaves; UHI; GIS

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1. Introduction

Overheating is a growing concern for the public health, urbanism, architecture and engineering disciplines, as cities have to face rising temperatures due to climate change. The latest report of the Intergovernmental Panel on Climate Change (IPCC) states that in the period of 2011–2020, the global surface temperature is already 1.1 °C higher than in 1850–1900 [1] and looks at southern Europe as one of the regions where summer temperatures will rise sharply [2]. Recent examples of this tendency were the last two summers 2022 and 2023. The summer of 2023 is considered to be the warmest summer globally with an average temperature in Europe of 19.63 °C, 0.83 °C above the average for the last 35 years [3]. The summer of 2022 was also very warm in Europe and was characterized specifically because, during it, there were very intense, long and consecutive heatwaves [4].

Specifically in Spain, where this study was conducted, the Spanish National Research Council (MNCN-CSIC) shows that the summer 2022 was the hottest on record, and during it, Spain experienced record-breaking heatwaves [5] that caused high associated mortality (the longest heatwave of 2022 was associated with 11,324 deaths (95% CI = 7908–14,880) [6]).

This increase in outdoor temperatures is especially exacerbated in the context of cities, due to the Urban Heat Island effect (UHI) [7]. UHI relates to the effects of the built environment on the temperature and humidity of the urban environment [8], which can raise outdoor temperatures in urban environments up to 2–4 °C higher than in the surrounding rural areas [9]. This effect is especially intense during the night [10,11], so the use of natural ventilation to purge warm indoor air in dwellings could be compromised within cities [12]. United Nations projections establish that 66% of the world's population will be living in cities by 2050 [13], with a growth trend in the future, entailing further urbanisation [14]. If not controlled, this growth will increase global warming and enhance the UHI effect in cities [15], a phenomenon that also can exacerbate heat-associated mortality, especially among the elderly, who are known to be most vulnerable to extreme temperatures [16,17].

In the context of global warming, the analysis presented in this study focuses on the temperate oceanic region of Europe, where the widespread and severe summertime overheating of dwellings is a relatively new but urgent phenomenon [18]. Due to the generally mild summers and chilly nights, indoor overheating was not a major issue [12]. However, in recent decades and due to increasing temperatures, energy demand loads have increased in summer in these areas of Europe [19], and in the future, heating demand is expected to decrease while cooling demand increases [20].

Because of that trend, a growing number of households are installing air conditioning (AC) devices to face global warming [21]. Even so, it is widely accepted that the incorporation of these systems cannot be the only adaptation approach [22] because these systems increase energy consumption [2], enhance warming conditions and the UHI effect [23], and are not a solution for vulnerable people (in energy poverty) as they cannot afford the associated energy costs [24].

Nowadays, in temperate Europe, the most common strategies for retrofitting building thermal envelopes include replacing windows with more energy-efficient ones and adding thermal insulation to façades, roofs and floors [25], with the main goal of reducing heating energy demand and consumption while maintaining adequate indoor environmental conditions during the winter. However, it is necessary to assess buildings' performance during summer by analysing which building parameters specifically influence overheating (like location in the building (floor level) [26–29], orientation of the main façade, area of windows [30,31], ventilation [32,33], shading systems [31,34], envelopes [35] and occupants' behaviour [12,36]) and to advance the research on passive strategies for renovating existing buildings and constructing new ones, focusing on reducing indoor overheating in summer to minimize the AC necessity to face high outdoor temperatures.

Regarding the passive strategies for adapting buildings to warming, recent research developed in this line shows that roofs play an essential role in indoor overheating, as several studies have found that the highest overheating in residential buildings occurs in dwellings located on the top floors under the roofs [26–29,37] and in the UHI effect, since they represent approximately 20–25% of urban surfaces and have a great influence on the air temperature of their surroundings [38]. Therefore, different systems and materials are being investigated to improve roofs, such as cool roofs and the integration of phase change materials or nature-based solutions such as green roofs [38], but there is still a lot of research to be developed.

For all this building performance assessment, different studies have shown the relevance of modelling the urban climate when assessing building performance, especially during summer, because of different findings: heat emissions from air conditioning units in cities can increase the local temperatures by up to 0.6 °C [39]; mean radiant temperature presents higher values for nighttime in the densely built-up city centre than in the suburbs with more open structures [40]; the hours of indoor overheating in dwellings increase on average by 7.52% when considering the effect of the urban context on outdoor temperatures [37]. Therefore, to evaluate the thermal and energy performance of a building, it is essential to consider its urban context, as it fundamentally influences outdoor temperatures, building energy demand, indoor and outdoor comfort, and citizens' quality of life [41]. This urban modelling can be conducted at different scales (neighbourhoods, blocks, etc.) according to the study's objective [42]. Evaluating buildings without considering their urban context could lead to underestimating overheating or cooling loads and result in adaptation strategies that may not be sufficiently adjusted for the warm climate.

In this context, the main objectives of this research are the diagnosis of indoor overheating in different residential typologies at an urban scale and the evaluation of the thermal envelopes' refurbishment as a measure to reduce it. The results are derived from energy simulations of residential typologies in Pamplona (a city in the North of Spain) during an extremely warm summer with heatwaves (2022), considering the effect of microclimate at a neighbourhood scale.

The specific research objectives of this research are

- To calculate the impact of building parameters on indoor overheating hours (IOH);
- To analyse which residential typologies are more vulnerable to overheating;
- To quantify the IOH reduction when the thermal envelopes of residential buildings are refurbished to meet the standards required by current energy regulations;
- To compare the IOH reduction between the retrofitting of thermal envelopes using traditional systems or incorporating nature-based solutions (green roofs).

Regarding the overheating assessment, this work develops a complete overheating diagnosis methodology at the city scale, with results per dwelling based on a wide spectrum of residential building typologies and considering the microclimate in the weather files. In relation to the retrofitting of thermal envelopes, most of the previous studies were focused on analyzing energy-related aspects and greenhouse gas emissions in buildings [43], paying less attention to thermal comfort in vulnerable dwellings [44]. Therefore, this study focuses on the evaluation of indoor overheating and indoor temperatures in dwellings, developing a quantitative comparison at an urban scale between the current state of residential buildings and retrofitting scenarios using traditional systems (high insulated envelopes) and nature-based solutions (green roofs), with a focus on the most vulnerable dwellings in the city.

2. Materials and Methods

The urban-scale methodology developed in this article has two parts: first, a diagnosis of the current indoor overheating in Pamplona's dwellings and second, a proposal of retrofitting strategies to reduce this indoor overheating.

Both parts are based on two transversal elements: (i) residential typologies, the definition and detection of which were carried out to representatively cover all the buildings in the city, and (ii) the microclimate weather files developed for each neighbourhood within the city.

First, the diagnosis of current overheating in dwellings for the summer of 2022 is carried out. For this purpose, the built characteristics and parameters were defined for each built period associated with the different and successive energy regulations in Spain. With the parametrization of these characteristics, the models of residential typologies were simulated, and the results were linked to the real sample of the studied city to develop the overheating assessment. This diagnosis methodology is described in depth in a previous article developed by the authors [37]. This article extends this methodology so that it can be applied at the urban scale and replicated: four built periods are considered (as opposed to the two previously considered), new residential typologies are identified (which increases the accuracy of the results between these and the real buildings) and newly built parameters of the dwellings are studied in order to analyse their relationship with indoor overheating. Considering all this, the overheating data are analyzed to identify the dwellings most vulnerable to overheating in the city. This diagnosis methodology is elaborated to be replicated in other Spanish cities, as well as in other Southern European cities with similar urban developments.

After the diagnosis, three scenarios for retrofitting the envelopes of dwellings are developed as strategies to reduce overheating. For this purpose, different types of thermal envelopes are defined, both with traditional systems and with the inclusion of nature-based solutions (NBS). After that, the models of residential typologies were parameterized and simulated, and the results were linked to the actual city sample, focusing on the dwellings previously identified as the most vulnerable. Finally, the results of the retrofitting scenarios were compared with the current state to quantify the improvement of dwellings in relation to indoor overheating.

The methodology of the study is depicted and summarized in Figure 1.

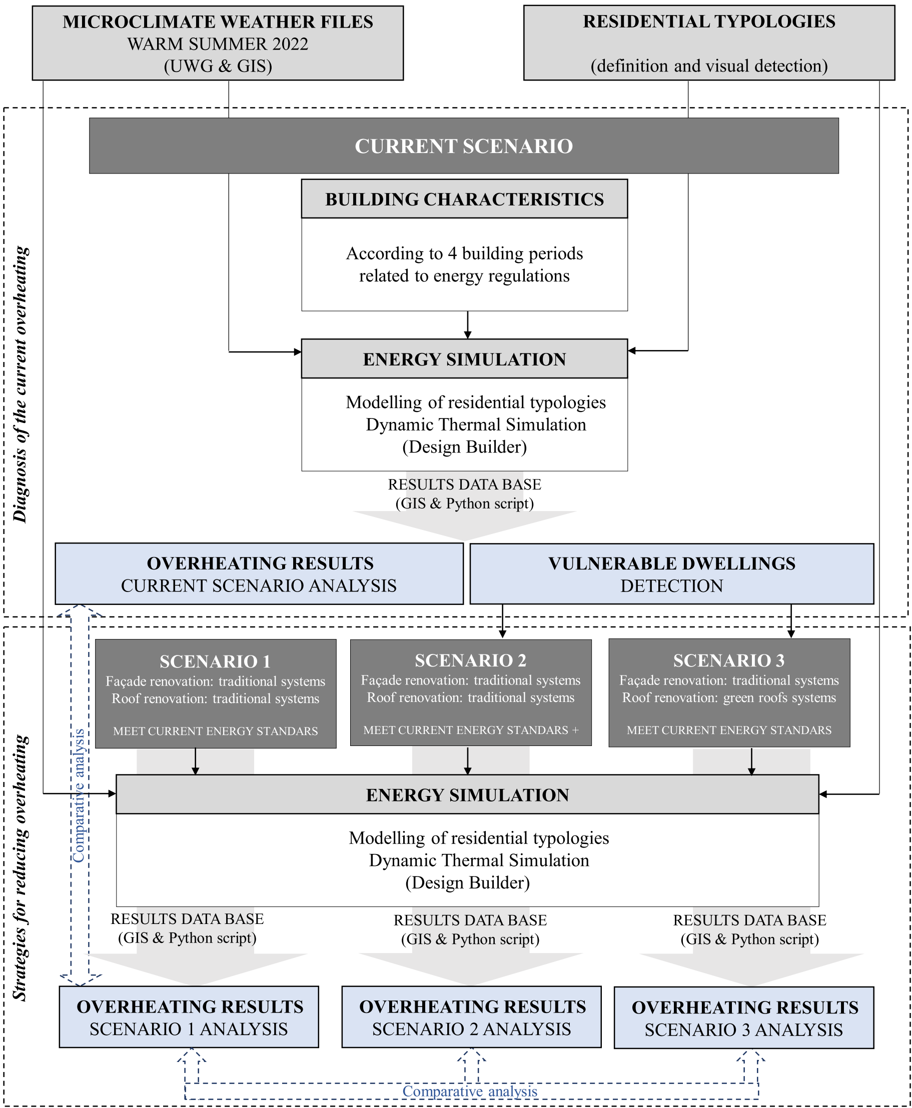


Figure 1. Flow chart of the methodology developed in this study.

2.1. Case Study

The case study is the city of Pamplona, located in the north of Spain. It has 97,018 dwellings [45] distributed in 14 neighbourhoods (Figure 2). In this research, 12 neighbourhoods with 85,812 dwellings in total were studied. Two neighbourhoods were excluded from the study: N13 because it is under construction and N14 (the old city centre) because the residential typologies and building parameters are very heterogeneous.

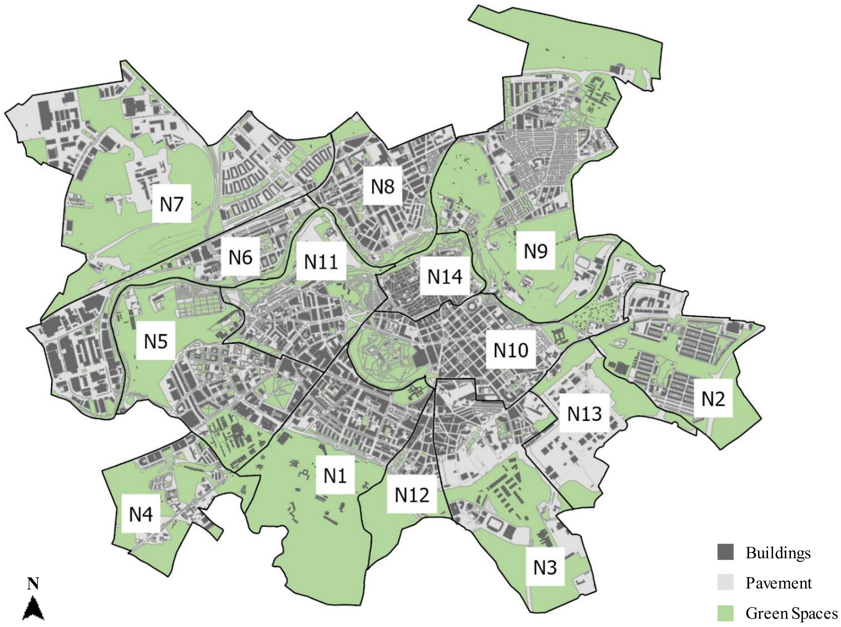


Figure 2. Pamplona with its 14 neighbourhoods.

2.2. Climate

Following Koppen–Geiger classification [46], the city where the study is developed is Cfb climate-temperate oceanic (coldest month averaging above 0 °C, all months with average temperatures below 22 °C, at least four months averaging above 10 °C and with no significant precipitation difference between seasons). In Pamplona, according to the 1980–2010 climate series, the mean temperature in summer (from 1 May to 30 September of ASHRAE IWEC2 [47]) is 17.9 °C, the mean of maximum temperatures is 24.7 °C and the mean of minimum temperatures is 12.3 °C. July and August are the warmer months with a mean of maximum temperatures of 28.3 °C and 31.2 °C, respectively.

In Spain, the State Meteorological Agency (AEMET, an acronym in Spanish) defines heatwaves based on daily maximum temperature. For Pamplona, with a temperate climate, a heatwave occurs when the daily maximum temperature exceeds the limit of 36 °C for three or more consecutive days. The year 2022 was selected in this study as an extremely warm summer that could represent the trend of future summers. It was selected because, in Pamplona, it was one of the warmest summers of the last 10 years, as a consequence of climate change, with 41 days of heatwaves distributed during June, July and August [48]. Table 1 summarises the mean temperatures for the whole summer period considered and each month.

Table 1. Summary of outdoor temperatures in Pamplona during summer 2022 (from May to September).

Period	Mean of Mean Temperatures	Mean of Maximum Temperatures	Mean of Minimum Temperatures
Summer 2022	20.6	27.7	15.3
May 2022	17.8	23.9	12.1
June 2022	21.4	28.2	15.8
July 2022	23.7	31.4	17.5
August 2022	23.3	30.8	16.5
September 2022	18.8	24.9	13.7

Temperatures obtained from METEONAVARRA [49], an open-access website from the Government of Navarre for downloading weather data from weather stations.

Microclimate Consideration

The tool to consider the microclimate of each neighbourhood was the Urban Weather Generator (UWG), which is a tool that uses the weather data of a rural site to calculate the temperatures of an urban city site, estimating the global effect of UHI on the energy performance of neighbourhoods or even cities [50]. To obtain microclimate weather files, sensitivity studies [51,52] show that the main input parameters for the simulation are (i) site coverage ratio (SCR); (ii) façade-to site ratio (FSR); (iii) tree coverage ratio (TCR); (iv) vegetation coverage ratio (VCR); (v) thermal properties of building materials, mainly albedo of roofs, walls and roads; (vi) and non-building sensible anthropogenic heat, mainly from traffic. In addition to these parameters, in this study, others were implemented in UWG as in other previous studies [10,50]: average building height (H) and vegetation albedo. These inputs were obtained in the Spanish cadastre (urban ground covered in grass and in trees, perimeter of building footprint, building height and area of the neighbourhood). Albedo values for roofs and walls were obtained by identifying the building materials with the help of Google Street View and considering existing literature for the albedo and emissivity values [50]. The vegetation and road albedo were also considered as a fixed value (0.4 and 0.2, respectively) for all neighbourhoods based on existing literature [50], and the anthropogenic heat generation was considered fixed for all neighbourhoods, as in other studies (25 w/m^2) [51]), because there were no data were available. Table 2 shows the values of each parameter used to modify the 2022 base file for each neighbourhood, with 12 microclimatic weather files in total).

Table 2. Values for the urban variables for each neighbourhood.

Neighbourhood	H (m)	SCR (0–1)	FSR (0–1)	TCR (0–1)	VCR (0–1)	Roof Albedo (0–1)	Wall Albedo (0–1)
N1	25.45	0.34	0.57	0.05	0.25	0.45	0.6
N2	10.38	0.17	0.18	0.02	0.47	0.29	0.63
N3	18.09	0.27	0.35	0.01	0.08	0.41	0.51
N4	12.51	0.1	0.12	0.01	0.63	0.45	0.66
N5	21.48	0.27	0.29	0.05	0.3	0.52	0.57
N6	18.18	0.28	0.15	0.02	0.28	0.2	0.44
N7	13.49	0.19	0.07	0.01	0.22	0.47	0.72
N8	16.23	0.28	0.42	0.02	0.25	0.49	0.8
N9	9.59	0.2	0.23	0.04	0.31	0.5	0.6
N10	15.27	0.28	0.42	0.03	0.28	0.29	0.45
N11	24.18	0.21	0.36	0.05	0.3	0.56	0.66
N12	21.84	0.24	0.36	0.03	0.4	0.53	0.6

When comparing the neighbourhood microclimatic files with the base weather file (i.e., 2022 weather file without considering the effect of microclimate), a significant difference in temperatures was found, particularly at night: considering the average of all neighbourhoods, outdoor temperatures are 1.3 °C higher during the day and 4.9 °C higher at night. When comparing the 12 microclimatic files with each other, no significant differences were observed due to the scale of the analysis.

2.3. Residential Typologies

Fourteen different residential typologies were detected within the city through visual detection per building using SITNA platform [53] (Spanish acronym of "Sistema de Información Territorial de Navarra", is a public and online resource in charge of the management and dissemination of geospatial and cartographic information) and Google Earth.

These residential typologies were developed in the previous project PrestaRener [54] and correspond to the most developed buildings in Spain. These residential typologies were validated and used in successive publications and research [24,55]. The spatial characteristics of each typology are described in Table A1, and Figure A1 (Appendix A) shows the residential typologies graphed in the city's urban plan.

Within the city, the urban contexts in which the typologies are located are very different, so it was not feasible to simulate all of them in the models. Even so, the interactions with the surroundings are considered through the microclimatic weather files (developed with the UWG tool), where different urban parameters were considered, as explained before (Section 2.2, Microclimate Consideration).

2.4. Residential Buildings' Current Scenario

For the analysis of the *current scenario* of the dwellings, four building periods were established based on different energy regulation requirements in Spain:

- No regulation period (<1980): buildings built prior to 1980 (the majority were built between 1940 and 1980). The energy requirements for this time period are based on the analysis of real projects [24], as there were no energy regulations.
- CT-79 period: buildings built between 1980 and 2006 following the first energy regulation standard in Spain- NBE CT-79 [56], which was developed as a consequence of the 1970s energy crisis.
- CTE 2006 period (2007–2019): buildings built between 2007 and 2019 following the Spanish Technical Building Code (CTE, according to its Spanish acronym) [57], which appeared as a consequence of the European Energy Efficiency Directive of 2002 [58].
- CTE 2019 period (after 2020): buildings built after 2020 following the Spanish Technical Building Code with the 2019 update, with the objective of meeting the nZEB standard in new and refurbished buildings [57].

Table 3 shows the characteristics of the four envelopes developed for complying with the energy requirements within each building period. Knowing the year of construction of each building, the corresponding envelope characteristics were assigned to them for the simulation.

The variable related to occupant behaviour was considered through the ventilation schedule and the solar shading performance, considering the common uses during summer in temperate climates and reported in surveys of previous studies such as the one presented in [29]: occupants mainly use solar shading protections when solar radiation is directly hitting the windows (in the simulations, it has been considered that the solar shading systems are fully down when the diffuse radiation is over 150 w/m^2, where this value is an estimation in relation to the average annual diffuse radiation of the IWEC2 weather file, which represents the 1980–2010 climatic series [47]); the users usually open the windows for ventilation at night or early in the morning when the outdoor temperatures are lower than indoor temperatures (in the simulations, ventilation is considered through "Calculated Natural Ventilation" with the "temperature" control mode, that is, windows are open—with a free aperture of 15%—as long as outside temperature is lower than inside temperature). In addition, the mandatory indoor air quality (IAQ) requirements are considered in the periods of CTE 2006 and CTE 2019. Dwellings are considered not to have air conditioning.

Table 3. Values for energy simulations and models' performance.

Energy Regulation Built Period	Ufaçade [a] Uroof (W/m^{2}K)	Uglass (W/m^{2}K)	Airtightness [d] Flow Coefficient (1 Pa)	Solar Shading System	Ventilation Schedule
No regulation <1980	1.39 2.9	5.7 [b]	Walls = 0.0001 kg/s m^2 Windows = 0.00014 kg/sm	Blinds with low reflectivity slats	Calculated natural ventilation: 24 h
CT-79 1980–2006	0.73 0.55	3.5 [b]	Walls = 0.0001 kg/s m^2 Windows = 0.00014 kg/sm	Blinds with medium reflectivity slats	Calculated natural ventilation: 24 h
CTE 2006 2006–2019	0.58 0.29	3.5 [c]	Walls = 0.00004 kg/s m^2 Windows = 0.00006 kg/sm	Blinds with medium reflectivity slats	Calculated natural ventilation: 24 h and 9:00–23:59: 0.63 ac/h
CTE 2019 >2020	0.30 0.19	1.7 [c]	Walls = 0.00001 kg/s m^2 Windows = 0.00001 kg/sm	Blinds with medium reflectivity slats	Calculated natural ventilation: 24 h and 9:00–23:59: 0.4 ac/h

[a] The impact that thermal bridges have on these façades is considered. No regulation period and CT-79 period: thermal bridges worsen the transmittance (U) by 30%; CTE 2006 period: thermal bridges worsen the transmittance (U) by 20%; CTE 2019 period: thermal bridges worsen the transmittance (U) by 10%. [b] Window frame without thermal break. [c] Window frame with thermal break. [d] The ventilation was considered through the calculated natural ventilation mode using the EnergyPlus Airflow Network. With this mode, the infiltrations are not calculated as a constant (or scheduled) value; they are defined through a specific flow coefficient through the surface itself, which could be caused by cracks or by general fabric porosity and cracks between windows, vents and doors and through the main wall or roof surface.

2.5. Residential Buildings' Retrofitting Scenarios

In order to evaluate the influence that the renovation of thermal envelopes has on the reduction of IOH, three scenarios were considered:

- SCENARIO 1: All residential buildings in the city, built before the first Spanish Technical Building Code (CTE 2006), improve their envelopes to meet the standards required by current energy regulations (CTE 2019).

After *Scenario 1*, with all dwellings complying with the Spanish Technical Building Code (2006 or 2019 version), two specific scenarios were proposed for the dwellings detected as more vulnerable to suffering higher overheating (i.e., dwellings with one orientation located on top floors):

- SCENARIO 2: Vulnerable dwellings improve their envelopes with traditional systems and with high insulation thicknesses in their roofs.
- SCENARIO 3: Vulnerable dwellings improve their envelopes by incorporating nature-based solutions in their roofs (green roofs).

Table 4 shows the characteristics of the roofs and façades considered in each retrofitting scenario. The rest of the envelopes' characteristics and the performance of the dwellings are considered as in the CTE 2019 period (Table 3).

Table 4. Characteristics of the façades and envelopes of each retrofitting scenario.

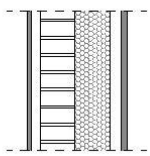
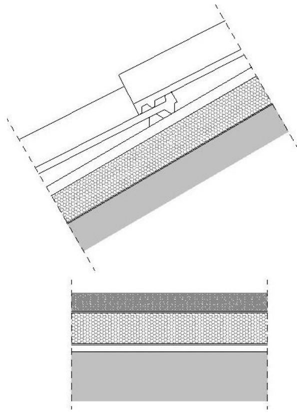
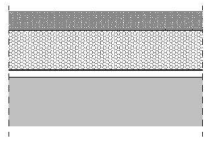
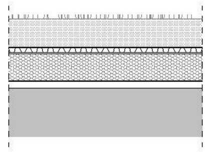
Component	U (W/m^{2}K)	Description	Detail
Facade Scenario 1 Scenario 2 Scenario 3	0.30	Ventilated façade: 12 cm of insulation ceramic tiles (finishing material)	

Table 4. *Cont.*

Component	U (W/m^{2}K)	Description	Detail
Roof Scenario 1	0.19	Flat roof or pitched roof: 16 cm of insulation tiles or gravel (finishing material)	
Roof Scenario 2	0.16	Flat roof: 20 cm of insulation gravel (finishing material)	
Roof Scenario 3	0.21	Extensive green roof: 14 cm of insulation 15 cm of soil (LAI 2.7) grass (finishing material)	

2.6. Energy Simulation Development

The fourteen residential typologies were modelled following the spatial and dimension characteristics in Table A1. Each dwelling was considered as a thermal zone because of the urban scale of the research [59]. To accept this simplification, this work is based on previous studies, which indicated that, when rooms do not have an active air conditioning system and the doors of all rooms are usually open, it is possible to consider the dwellings as one single thermal zone [60]. For each residential typology, results for two dwellings were obtained: one for a dwelling located in an intermediate floor (IF) and another for a dwelling on a top floor (TF) under the roof. The simulations were carried out using microclimatic weather files for the year 2022 obtained from the UWG for each neighbourhood. The considered simulation period runs from 1 May to 30 September [61].

To simulate the current scenario of the residential buildings, the fourteen residential typologies were modelled with their corresponding envelopes linked to their built period (Table 3), in 8 different orientations (main façade of dwellings facing north, northeast, northwest, south, southeast, southwest, east or west), with and without blinds and wit hand without balconies, resulting in 1792 building simulation cases. Each model was simulated for the 12 microclimate weather files, resulting in 43,008 simulation results of IOH.

To simulate the retrofitting scenarios, the fourteen residential typologies were modelled with their corresponding envelopes linked to their retrofitting scenario (Table 4), in the 8 different orientations, with/without blinds and with/ without balconies, resulting in 1344 building simulation cases. Each simulation case was simulated for the 12 microclimate weather files, resulting in 32,256 simulation results of IOH.

Not all of these combinations exist in the real sample of Pamplona dwellings, and others are repeated for more than one dwelling. Simulation results were applied to the real sample of dwellings in the city for each scenario using GIS tools (ArchGisPro version 3.2.0.).

Design Builder software was used to generate the models and EnergyPlus (version 9.4), with a custom script developed in Python was used to perform all the simulations and prepare the results so that they could be analyzed in the GIS.

2.7. Statistical Methods and Overheating Metrics

The overheating assessment was based on the comparison of percentages of indoor overheating hours (%IOH) of dwellings, calculated following the EN 16798-1:2019 adaptive threshold (European standard applied in Spain) [62] for naturally ventilated buildings in free-running mode and Category IEQII of expectation. Category IEQII of expectation is related to a medium level of expectations that normal occupants may have and can be used for existing, new or renovated buildings. Through them, the daily maximum acceptable operative temperature is obtained (based on the outdoor running mean temperature) to calculate the percentage of hours of indoor overheating (%IOH).

The maximum acceptable operative temperature (TMAX) was calculated through the following formula:

$$\mathrm{TMAX\ (Category\ II)} = 0.33\,\mathrm{TRM} + 21.8 \tag{1}$$

Outdoor running mean temperature (TRM) is defined as the exponentially weighted running mean of daily outdoor temperature:

$$\mathrm{TRM} = (1 - 0.8)\left(T_{ed-1} + 0.8T_{ed-2} + 0.8^2 T_{ed-3} + \ldots\right) \tag{2}$$

where

Ted-i = daily mean outdoor air temperature for the i-th previous day (it has been calculated for the previous 7 days).

This standard does not establish the limit of IOH that should not be exceeded in a dwelling, so %IOH were used as a comparison between dwellings, and to have a limitation reference, the one established in the CIBSE TM-59 standard for the %IOH was considered [61]: dwellings should not exceed 3% of IOH.

In relation to the diagnosis of interior overheating, six building parameters (exposure variable) and their influence on the IOH were evaluated through descriptive analysis and a multiple linear regression model. Originally, they were not categorical: the built period (construction year of the dwelling), main orientation (one of the eight possible orientations considered) and number of orientations of the dwelling (1, 2, 3 or 4 orientations) were discrete variables; the floor level variable was dichotomous (top floor or intermediate floor); and the window area and dwelling area variables were continuous. For the statistical analysis, all of them were transformed into categorical, and to develop the multiple linear regression model, this mix of categorical variables was controlled by encoding the ordinal and nominal variables with more than three categories. In addition, the IOH of the different building typologies was comparatively analyzed according to their representativeness.

The retrofitting scenarios were evaluated comparatively through descriptive analyses and a nonparametric statistical test that compares two paired groups (Wilcoxon).

Statistical analyse were developed using Python and STATA statistical package version 16 (College Station, TX, USA; Stata Corp LLC), and results were mapped through the GIS tool (ArchGisPro version 3.2.0). Statistical significance was set at 0.05.

3. Results

3.1. Impact of Building Parameters on IOH

The analysis for quantifying the influence of the building parameters on the percentage of indoor overheating hours (%IOH) was developed through a correlogram, a multiple linear regression model, and comparative box-plots between the categories of each parameter studied (built period, floor level, main orientation, number of orientations of the dwelling, window area and dwelling area).

The %IOH was calculated through the EN 16798-1:2019 adaptive threshold for 2022, an extremely warm summer, of all dwellings of the city considering the microclimate effect.

Figure A2 (Appendix A) shows this %IOH on the city plans (intermediate floor and top floor) for the 2022 weather files.

First, a comparative box plot of the %IOH of each category within parameters, is shown in Figure 3. This is a descriptive analysis that shows the distribution of the data and the comparative trend between the categories of each exposure variable. The graphs show that most of the categories present an average %IOH greater than 10%. The highest %IOH values are when the dwellings are grouped according to the "number of orientations", specifically in the "one orientarion" category (19.2 %IOH on average); the lowest values are when the dwellings are grouped by the built period in the built periods after CTE 2006 (2.9 %IOH on average).

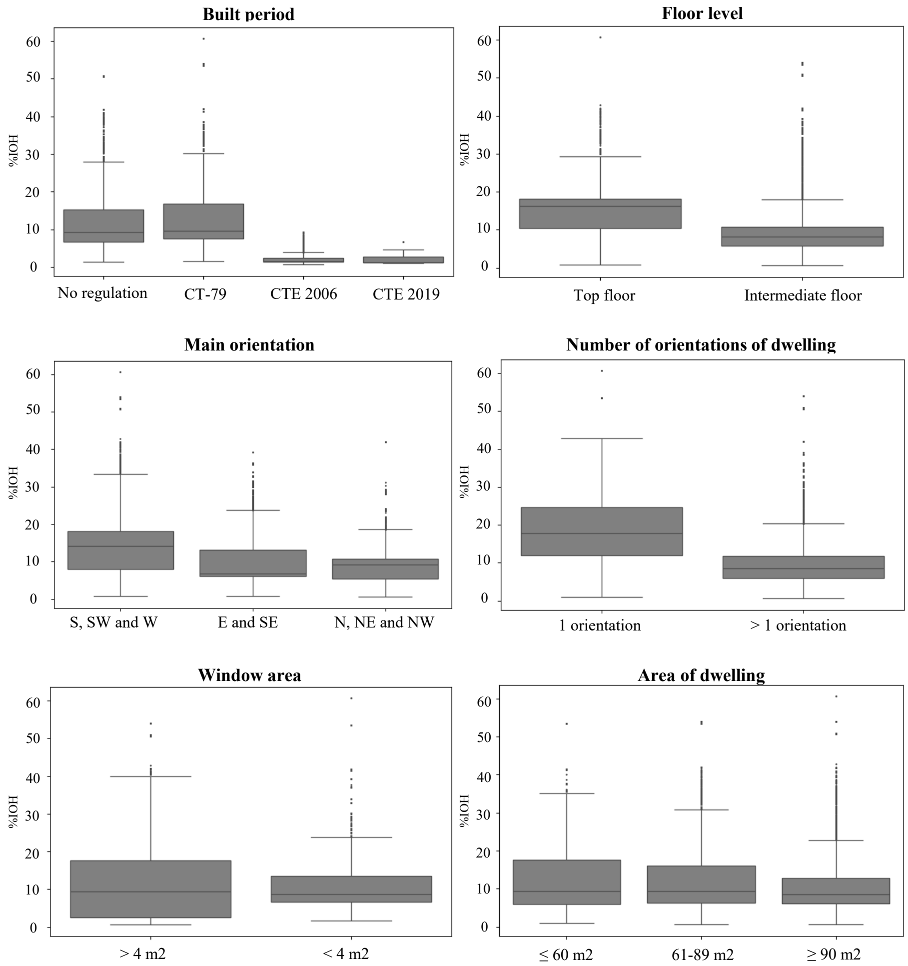


Figure 3. Comparative box−plots between the categories of each parameter studied.

Then, to expand these results, a multiple linear regression model was developed. This analysis expresses the causal relationships between each of the categories within each independent variable and the %IOH, quantifying which are the ones that produce more %IOH in the dwellings. The results are shown in Table 5 and are in line with the previous descriptive analysis in the box plot. All the parameters present a statistically significant relationship with the dependent variable (%IOH), but the categories of each parameter that influenced more %IOH are being built after the CTE 2006 reduced %IOH by 12%; being located in intermediate floors reduced %IOH by 5.4%; dwellings that have north, northeast and northwest as the main orientations presented 4.75% less IOH than those that faced south, southeast and southwest orientations; dwellings with more than one orientation showed a reduction in %IOH of 7.5% compared to those with only one; dwellings with a total window area smaller than 4 m^2 had 2.92% less IOH than those with an area bigger than 4 m^2; and dwellings larger than 90 m^2 had 0.89% less IOH than smaller ones.

Table 5. Adjusted percentage of %IOH according to different building parameters.

Parameters	Beta Coefficients	95% Conf. Interval	*p*- Value
Built period			
No regulation period	0 (Ref.)		
CT-79 period	−0.72	(−0.80 to −0.64)	<0.001
CTE 2006 period	−12.18	(−12.3 to −12.1)	<0.001
CTE 2019 period	−12.70	(−13.3 to −12.1)	<0.001
Floor level			
Top floor	0 (Ref.)		
Intermediate floor	−5.37	(−5.46 to −5.28)	<0.001
Main orientation			
S, SW and W	0 (Ref.)		
E and SE	−3.76	(−3.86 to −3.67)	<0.001
N, NE and NW	−4.75	(−4.83 to −4.66)	<0.001
Number of orientations of the dwelling			
1 orientation	0 (Ref.)		
>1 orientation (higher possibilities of ventilation)	−7.54	(−7.66 to −7.41)	<0.001
Window area			
>4 m^2	0 (Ref.)		
≥4 m^2	−2.92	(−3.03 to −2.80)	<0.001
Dwelling area			
<60 m^2	0 (Ref.)		
61–89 m^2	−0.51	(−0.35 to −0.65)	<0.001
>90 m^2	−0.89	(−0.74 to −1.04)	<0.001

In summary, although all the independent variables presented a statistically significant relationship with %IOH ($p < 0.05$), the building parameters that most promote overheating are being built before the CTE 2006 period (in the no-regulation period and in the CT-79 period), facing only one orientation (lower possibilities of cross-ventilation), being under the roof on the upper floor, facing S/W/SW as main orientation, window area larger than 4 m^2 and dwelling area smaller than 60 m^2, in this order of importance.

3.2. Analysis of Residential Typologies More Vulnerable to Overheating

First, an analysis of residential typologies was carried out based on the mean %IOH and representativeness of each typology within the city (Figure 4).

There is a great difference in residential typologies' representativeness: 71% of the dwellings in the city correspond to only three groups of residential typologies (typologies 11, 12 and 21), while the remaining percentage is distributed among 11 different typologies.

The mean %IOH of all typologies is 10.6%, and the mean of maximum %IOH is 22.8%. The typologies with the highest mean and mean of maximum %IOH are 33 (37.2% mean of IOH and 50.2% of maximum IOH), 12 (19.8% mean of IOH and 42.3% of maximum IOH), 15 (19.1% mean of IOH and 38.1% of maximum IOH), 34 (15.8% mean of IOH and 39.8% of maximum IOH), 31 (14% mean of IOH and 26.2% of maximum IOH) and 52 (12.6% mean of IOH and 23.2% of maximum IOH), in this order. However, in relation to their representativeness, only typology 12 has a significant representativeness of 12.3%, while the other groups do not even reach 5% of the representativeness within the city.

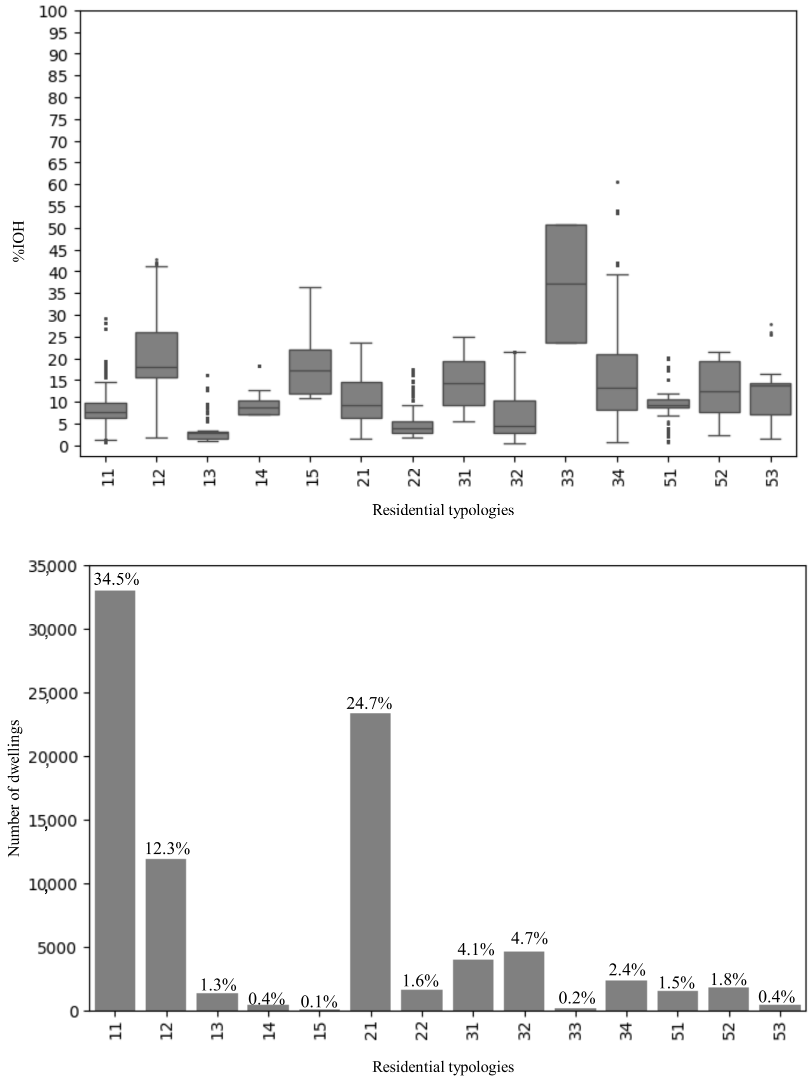


Figure 4. %IOH by residential typology (**top**) and number of dwellings by residential typology and mean (**bottom**).

In relation to the assessment of the building parameters that most promote IOH (Section 3.1.), only one of them is directly related to a specific residential typology, and it is the most correlated with IOH: the number of orientations of the dwelling. In comparison to dwellings that face only one orientation, with multiple orientations in a dwelling (which increases the potential for cross-ventilation), reduces %IOH by 7.54% (Table 5). Therefore, residential typologies with only one orientation (typologies 12, 13, 34) were identified as more vulnerable to suffering higher %IOH. They represent 16% of the city with an 18.5% mean of IOH. Between them, typology 13 has a low %IOH as it represents very few buildings in Pamplona, all of which are built with good thermal performance. Even so, it is considered vulnerable since it presents the most influential parameter in the IOH (it has only one orientation per dwelling).

Figure 5 shows the analysis of representativeness and %IOH within these residential typologies (12, 13, 34): the highest difference in %IOH between dwellings located on the intermediate floor and on the top floor is in the no-regulation period, as they do not have thermal insulation in the roofs. In the CT-79 period, although the thermal insulation in roofs is low, the difference in %IOH between floors is significantly reduced. The dwellings built after CTE 2006 have a significant reduction in %IOH, with values around 5% of IOH, despite having only one orientation.

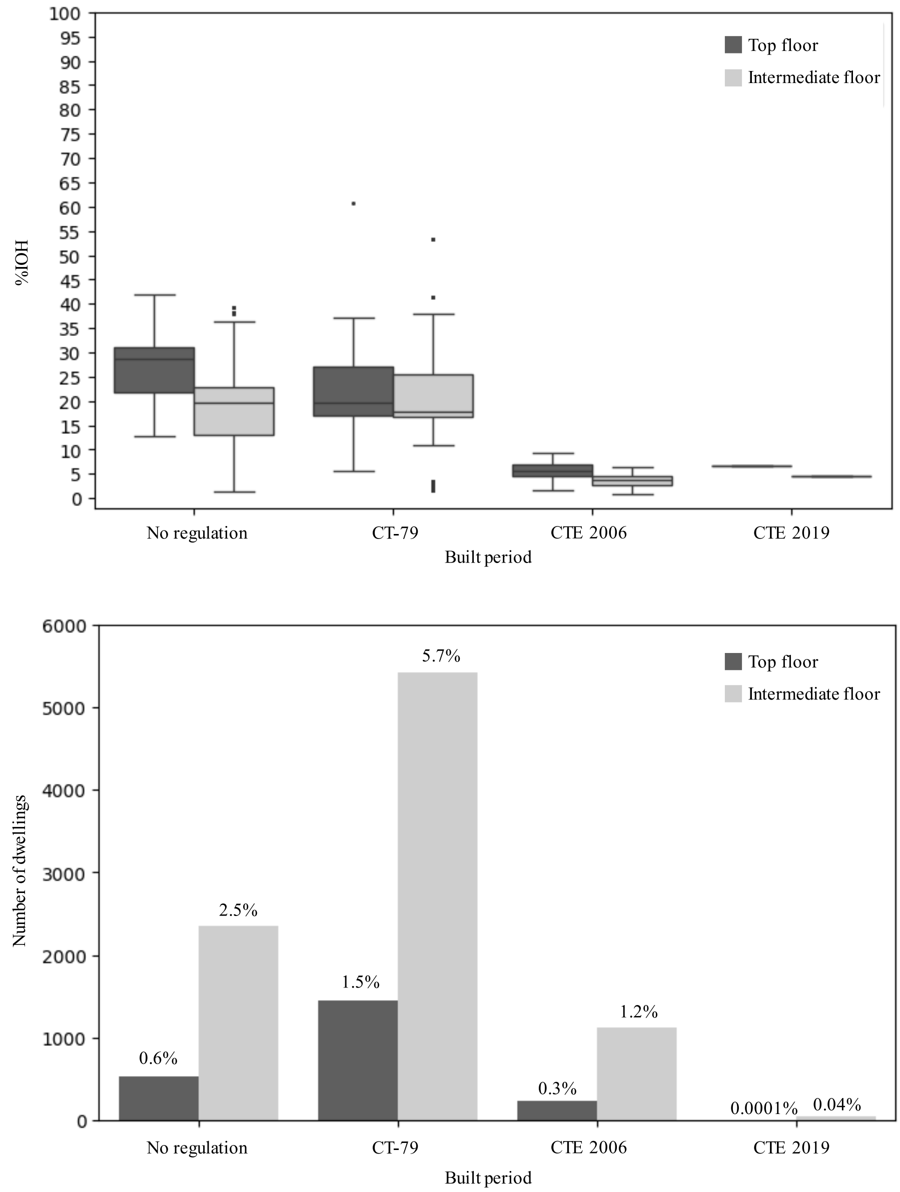


Figure 5. Mean %IOH of dwellings with one orientation by built period and floor level (**top**) and number of dwellings with one orientation in the city by built period and floor level (**bottom**).

In summary, the residential typologies considered as more vulnerable to higher %IOH are those with one orientation per dwelling (less ventilation possibilities) with 18.5% mean IOH, and within this group, those built before CTE 2006 and located on top floors of the buildings, with 23.7% mean IOH, more than twice the mean %IOH of the city.

Figure 6 shows the city plan with the dwellings that were built before CTE 2006 and those with one orientation located on top floors under the roof.

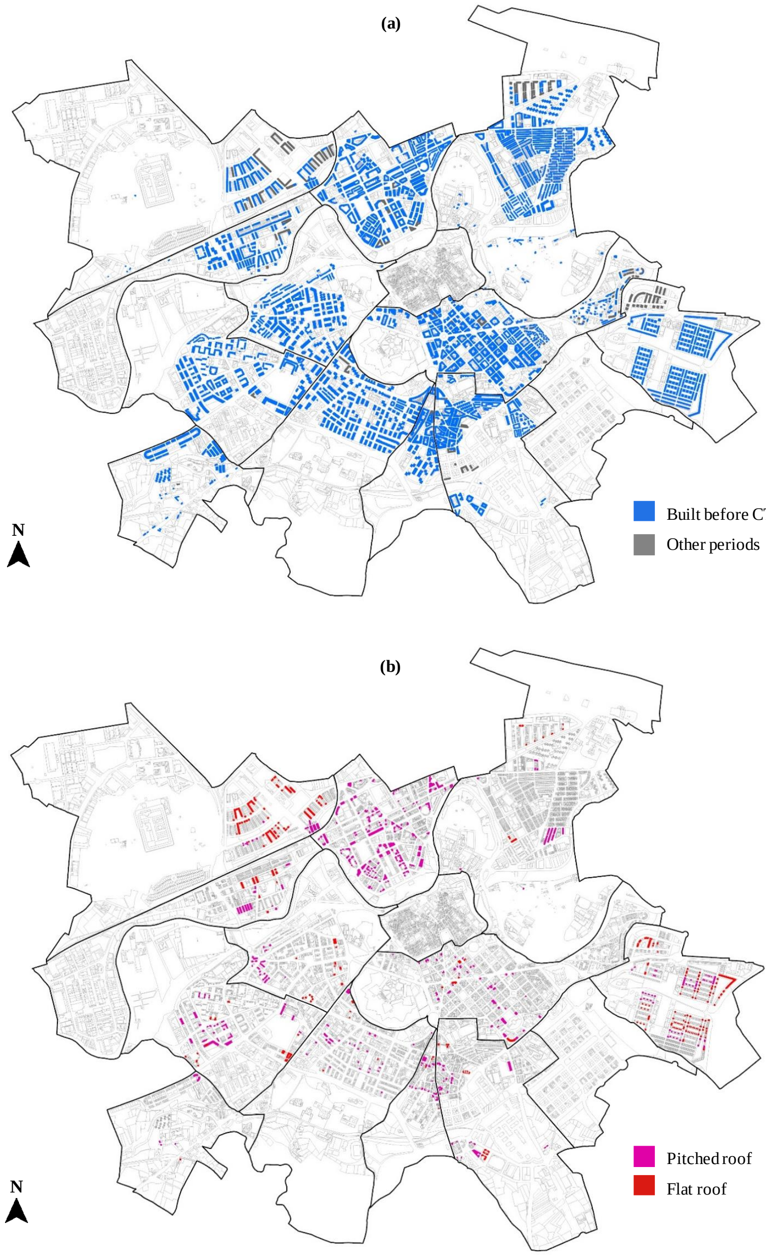


Figure 6. (**a**) Dwellings built before CTE 2006; (**b**) Dwellings most vulnerable to indoor overheating (dwellings with one orientation and located on top floors).

3.3. IOH Reduction in Retrofitting Scenario 1

Scenario 1 considers that all buildings built before CTE 2006 improved their envelopes to meet the standards required by the current energy regulations in Spain (CTE 2019). Figure 7 shows a %IOH comparison between the *Current scenario* of residential buildings and the refurbishment considered in *Scenario 1*. Table 6 shows the reduction in %IOH and in hours above the maximum limit accepted in each residential typology after the improvement considered in *Scenario 1*.

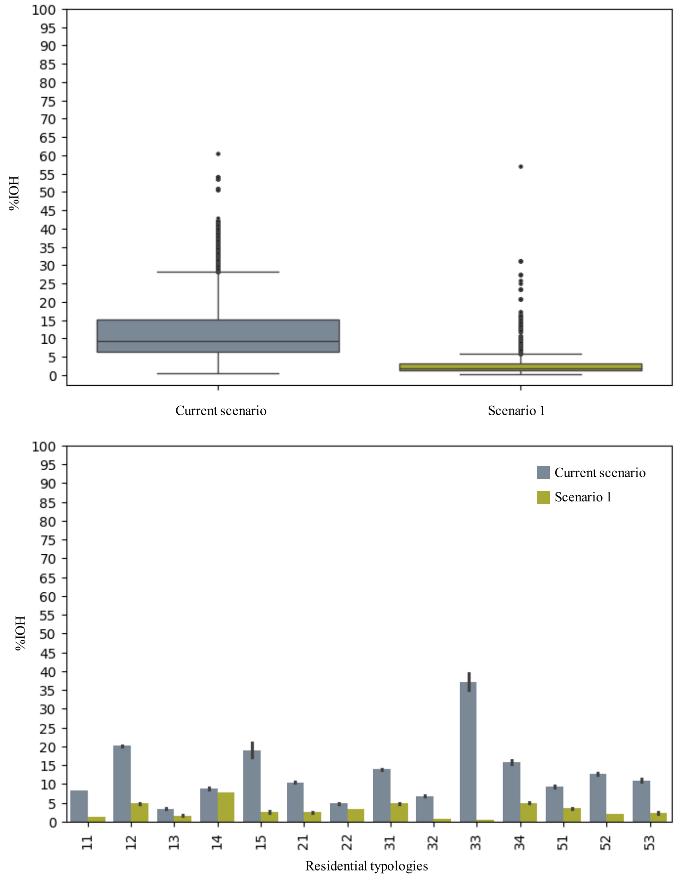


Figure 7. Comparison of %IOH between the *Current scenario* and *Scenario 1* in all refurbished dwellings (**top**) and by residential typology (**bottom**).

Table 6. Difference on indoor overheating between the *Current scenario* and *Scenario 1* by typology.

Typology	Representativeness		Current Scenario		Scenario 1		Reduction	
	n	%	%IOH	HE *	%IOH	HE *	%IOH	HE *
11	33, 471	34.5	8.33	305.78	1.32	48.4	7.01	257.39
12	11,933	12.3	20.15	740.01	4.80	176.3	15.35	563.71
13	1261	1.3	3.48	127.8	1.67	61.28	1.81	66.52
14	388	0.4	8.77	322.15	7.82	287.24	0.95	34.91
15	97	0.1	19.07	700.4	2.48	91.05	16.59	609.35
21	23,963	24.7	10.46	384.26	2.47	90.63	8.00	293.62
22	1552	1.6	4.83	177.21	3.43	125.78	1.4	51.42
31	3977	4.1	13.99	513.66	4.80	176.32	9.19	337.34
32	4559	4.7	6.81	250.11	0.89	32.67	5.92	217.45
33	194.04	0.2	37.19	1365.75	0.52	18.96	36.68	1346.8
34	2328	2.4	15.81	580.66	5.04	185.2	10.77	395.46
51	1455	1.5	9.27	340.47	3.52	129.27	5.75	211.19
52	1746	1.8	12.65	464.37	2.00	73.5	10.64	390.88
53	388	0.4	11.00	404.01	2.38	87.53	8.62	316.49

* HE: Hours of exceedance.

In the *Current scenario*, the mean of %IOH for all dwellings is 11.10% and its median is 9.23%. In *Scenario 1*, the overall mean is reduced to 2.51%, and the median to 1.97%. The means of %IOH between the two scenarios were compared using the Wilcoxon statistical test, showing that the difference between them is statistically significant ($p < 0.05$).

Analyzing the reduction in %IOH in *Scenario 1* by typologies, the greatest reductions occur in the typologies that in the *Current scenario* presented the highest %IOH: typologies 12, 15 and 33.

The most significant improvement occurs in typology 33, with a reduction of 36.67% and reaching almost zero overheating (0.52% IOH) in *Scenario 1*. Typology 12 reduces its %IOH by 15.36% and typology 15 by 16.59%.

For typologies 33 and 15, these results may mainly be due to two reasons:

On the one hand, both typologies have very little representativeness, and the few dwellings to which they refer were all built before there were any energy regulations in Spain (before 1980). In addition, both typologies (typology 33: dwellings with three orientations; typology 15: dwellings with two 90° orientations) represent dwellings with areas greater than 100 m^2, with large façade surfaces and a large number of windows, so the low energy performance of these envelope's components produce high %IOH in the *Current scenario*.

On the other hand, in *Scenario 1*, with the improvement in their envelopes, there was a reduced negative effect that these built parameters have on %IOH. Then, other characteristics of these typologies (large plan areas and several orientations per dwelling that promote cross ventilation) collaborated significantly in the reduction in the %IOH.

For typology 12, although its representativeness is higher, the significant reduction in %IOH is mainly because 95% of the dwellings of this typology were built before 1980, so their envelopes in *Current scenario* had very low thermal performance.

Figure A3 (Appendix A) shows the %IOH results for the *Scenario 1* on the city plans (intermediate floor and top floor).

3.4. IOH Reduction in Retrofitting Scenarios 2 and 3

This section examines strategies for lowering %IOH in the dwellings that are most vulnerable to overheating (dwellings with only one orientation and located on the top floors under the roof). The main aim of *Scenario 2* and *Scenario 3* is to improve the roofs of the buildings. Improving the parameter of "one orientation per dwelling" is not considered, since this would imply an intervention in the spatial distribution of the buildings, which is not feasible.

Scenario 2 involves the refurbishment of roofs with traditional systems and incorporating higher insulation thicknesses than those required by regulations. In contrast, *Scenario 3* proposes the renovation of roofs by incorporating green roof systems. Both scenarios focus on analysing vulnerable dwellings with flat roofs (since the installation of green roof systems is more economically and technically feasible for this type of roof) and meeting the requirements of CTE 2019.

Figure 8 shows a %IOH comparison between the *Current scenario*, *Scenario 1*, *Scenario 2* and *Scenario 3* for these dwellings. In *Scenario 1*, the mean %IOH for vulnerable dwellings with flat roofs is 6.86% and its median is 6.63%. In *Scenario 2*, there is no significant reduction, with a mean of 6.46% and a median of 6.26%. However, in *Scenario 3*, a greater reduction is achieved than in *Scenario 2*, with a mean of 4.42% and median of 4.12%.

Figure 9 shows a scatter plot that relates the %IOH of the dwellings and the mean indoor temperatures during the warmest month of the period analyzed (July 2022). The scatter plot shows that *Scenario 3* (retrofitting with green roofs) achieves a reduction in both %IOH and indoor temperatures in relation to *Scenario 2* (retrofitting with traditional systems and high thickness of insulation). For *Scenario 3*, most dwellings present around a 5% of IOH, while for *Scenario 2,* they are around 7% of IOH. Moreover, for low percentages of IOH (<3%), the refurbished dwellings in *Scenario 3* present lower temperatures than in *Scenario 1* or *Scenario 2*. Dwellings with 3% IOH, in *Scenario 1* and *Scenario 2*, present mean temperatures in July of 28.8 °C, while the same dwellings in Scenario 3 present average indoor temperatures of 28.4 °C. This shows that in *Scenario 3*, although the dwellings have hours above the maximum limit allowed (EN 16798-1:2019), they exceed this limit with lower temperatures than in *Scenario 2*.

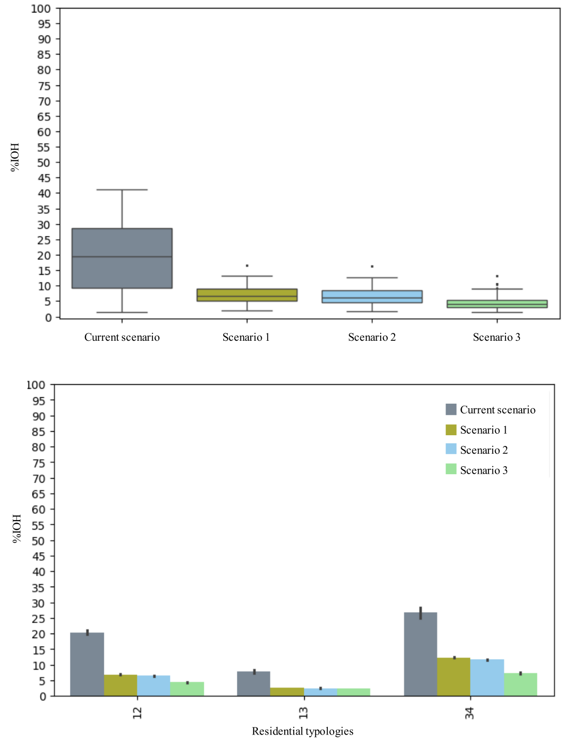


Figure 8. Comparison of %IOH between the *Current scenario*, *Scenario 1*, *Scenario 2* and *Scenario 3* in all refurbished dwellings (**top**) and by residential typology (**bottom**).

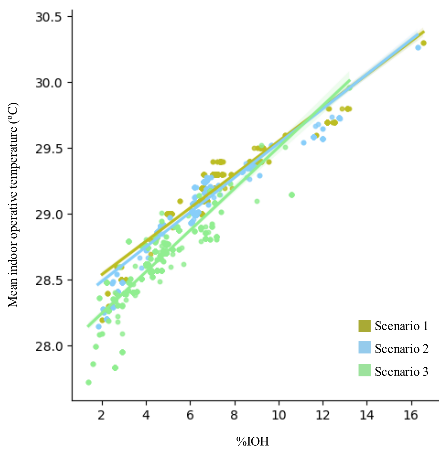


Figure 9. Correlation between %IOH and mean temperatures in *Scenario 1*, *Scenario 2* and *Scenario 3* (July 2022).

Figure 10 shows the comparison between *Scenario 2* and *Scenario 3* using a histogram of the distribution of the number of vulnerable dwellings in each range of mean maximum and mean minimum temperatures during July 2022.

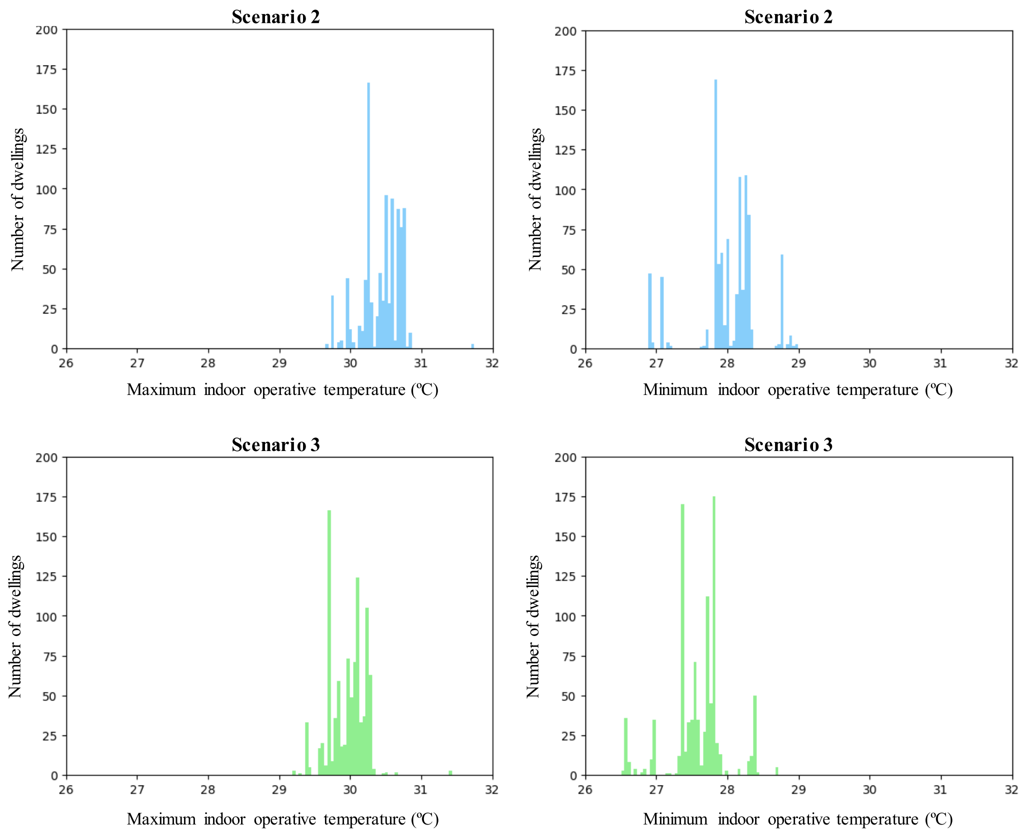


Figure 10. Distribution of vulnerable dwellings according to their mean maximum and minimum temperatures for Scenario 2 and Scenario 3 (July 2022).

Comparing the two scenarios of vulnerable housing retrofitting, it is observed that in *Scenario 3*, the graph moves to the left in both maximum and minimum temperatures, with a reduction of approximately 0.5 °C.

4. Discussion

This paper analyses the indoor overheating of residential dwellings in Pamplona (city located in the north of Spain) through a diagnosis methodology at the urban scale and presents different thermal envelopes' retrofitting scenarios as a strategy to reduce it. The results are derived from energy simulations of residential typologies in Pamplona (a location with temperate climate, Cfb) during an extremely warm summer with heatwaves (2022), considering the effect of microclimate at the neighbourhood scale.

The analysis of the dwellings' building parameters in relation to %IOH shows the importance of architectural design to prevent overheating: thermal envelope characteristics (especially roof insulation), plan design to enhance cross ventilation, size of windows, solar shading systems (especially in S/SW and W orientations), and the area of the dwellings are key building parameters that, if well designed, could reduce indoor overheating. Among these parameters, only one of them is directly related to a specific residential typology, which is the number of orientations, since the other parameters are related to all residential typologies. In the presented case study, having multiple orientations (which increases the potential for cross-ventilation), in comparison to only one orientation per dwelling, reduces %IOH by a 7.54%.

Therefore, residential typologies detected as more vulnerable to suffering from higher %IOH are those with only one orientation: they represent 16% of the city with 18.5% mean %IOH. Within these residential typologies, dwellings that present a higher %IOH are those built before CTE 2006 (the Spanish normative derived after the European Energy Efficiency Directive of 2002) and located on top floors under the roof, with 23.7% mean

IOH, more than twice the mean %IOH of the city. These results are aligned with previous research, which found that dwellings with one orientation presented 9.7% higher IOH than those with a double orientation [29], meet less CIBSE TM-59 criteria [33] or are 1 °C higher on average than those with only one orientation in highly insulated buildings [32]. Additionally, other research found that apartments located on top floors present 1.5% more IOH than those located on intermediate floors [29], are warmer than intermediate floors for more than 50% of summer hours [27], meet fewer CIBSE TM-59 criteria [26] and have mean temperatures that are up to 1.2 °C higher than in other floors [28].

In relation to the different thermal envelopes' retrofitting scenarios, the first one (*Scenario 1*) involves the renovation of the buildings' envelopes to meet current energy standards (CTE 2019), with a ventilated façade system with high insulation and airtightness and a traditional flat roof with high insulation. This envelope renovation reduces IOH by an average of 8.6% and up to 15.35% in the most vulnerable typologies. Regarding the roof improvement scenarios in vulnerable dwellings, the most favourable results with the greatest reductions of %IOH and indoor temperatures are obtained for *Scenario 3* (retrofitting by implementing green roof systems).

Due to climate change, existing buildings, which will be in use during future decades, were designed or are being designed for less severe climates than those expected in the future, so they will have to face more extreme conditions in summer, even in temperate climates. Hence, it is essential to evaluate the performance of dwellings under warmer temperatures to consider effective renovation measures or build new buildings prepared for these new conditions. This study provides results that may contribute to this challenge.

The research has shown that dwellings with one orientation do not have a good performance when outdoor temperatures are high and their refurbishment to reduce indoor overheating has few possibilities for improvement through passive measures. Therefore, their design should be specifically justified from the beginning so that adequate indoor overheating is ensured and so that this type of dwellings is not committed only to the installation of active systems, such as air conditioning, to achieve adequate indoor temperature conditions. In addition, it has been found that dwellings on top floors have higher overheating in comparison to those located in other floors of buildings, so future energy regulations may consider a specific justification, at least in terms of overheating, for dwellings located on the top floors.

In relation to retrofitting scenarios, highly insulated envelopes should be designed not only for winter scenarios but also for summer to reduce overheating, as in the case of this study, so as not to produce counterproductive results: previous studies have shown that if these highly insulated envelopes with high airtightness are not properly designed, they can lead to excessive overheating due to difficulty dissipating heat, prompting the installation of air conditioning systems and potentially increasing cooling demands [63,64]. In addition, the results show that renovating roofs with large insulation thicknesses, as is being carried out in the temperate region of Europe [65,66], is not the optimal solution to reduce indoor overheating, as other rehabilitation strategies such as green roofs are more effective.

Green roofs not only contribute to reducing indoor overheating, as this study has shown, but also to urban regeneration and adaptation to climate change by reducing the UHI effect [67,68]. A study developed in temperate climate showed that this reduction in the surface temperatures of green roofs represents a reduction in air temperature of up to 4 °C [69]. In addition, green roofs may collaborate to "renaturalize" cities (especially in congested metropolitan areas where there is a great lack of available space to establish green areas), which would lead to multiple multidisciplinary benefits such as air quality improvement when applied on a large scale [70], habitat creation to improve biodiversity in cities [71], urban water management [72], a reduction in urban noise [73], and spaces for recreation and interpersonal relationships [74].

While passive solutions provide good results in reducing overheating and are crucial for urban adaptation to climate change, it should be recognized that, during critical events like heatwaves in certain locations, combining passive and active cooling systems optimizes energy efficiency and is the only way to ensure the occupants' comfort [75]. In this regard, innovative refrigeration systems [76,77] are being developed as alternatives to traditional air conditioning, which may significantly contribute to achieving climate goals for 2030 and 2050.

The limitations of this study are mainly related to the methodology: a fixed value was used for anthropogenic heat from traffic in the UWG tool since there was no available data to adjust it by neighbourhood, and the visual identification of typologies and the main orientation of dwellings were used, which consume great effort and resources. In addition, due to the urban scale of the study, the dwellings were considered as a single thermal zone, so differences between bedrooms and living rooms could not be analysed.

Based on the detection of the dwellings most vulnerable to overheating, future work may be able to propose and analyze other different adaptation measures ("cool roofs", phase change materials, etc.) with the objective of reducing indoor overheating and improving the urban environment. Furthermore, future research may extend this case study by analyzing the proposed scenarios through the whole year to encourage decarbonization at urban scale [78]. To manage this work, the development of GIS tools is essential, as it allows the evaluation of large groups of buildings [79].

5. Conclusions

Indoor overheating in residential buildings has become an issue that is being analysed by several researchers and concerns public administrations around the world due to rising temperatures and more frequent and extreme heatwaves during recent summers, even in temperate climates.

This paper analyses the indoor overheating of residential dwellings in Pamplona (a city in the north of Spain) through a diagnosis methodology at an urban scale and presents different thermal envelopes' retrofitting scenarios, including nature-based solutions (NBSs). The results are derived from energy simulations of residential typologies in Pamplona (a city in the North of Spain with a Cfb climate) during an extreme warm summer with heatwaves (2022), considering the effect of microclimate at a neighbourhood scale.

In relation to the overheating assessment, this work develops a complete overheating diagnosis methodology at city scale (more than 80, 000 dwellings), with results per dwelling, based on a wide spectrum of residential building typologies and considering the microclimate in the weather files. Furthermore, this methodology is developed to be replicated in other Spanish cities, as well as in southern European cities with similar urban developments. Regarding the retrofitting scenarios, this study offers a quantitative comparison at an urban scale between the current state of residential buildings and the retrofitting scenarios using traditional systems (highly insulated envelopes) or nature-based solutions (green roofs), with a focus on the most vulnerable dwellings (i.e., dwellings with one orientation and located on top floors).

Regarding the overheating diagnosis, the impact that building characteristics have on indoor overheating hours (IOH) was assessed, concluding that those that most promote overheating on dwellings are being built before the CTE 2006 period (appearing as a consequence of the European Energy Efficiency Directive of 2002), facing only one orientation (lower possibilities of cross-ventilation), being under the roof on the upper floor with a S/W/SW orientation, having a window area larger than 4 m^2, and the dwelling area being smaller than 60 m^2, in this order of relevance. Among these parameters, only one of them is directly related to a specific residential typology: the number of orientations of the dwelling. Therefore, the residential typologies most vulnerable to overheating are those that have only one orientation, and which represent a 16% of the city, with a 18.5% mean %IOH. Within these residential typologies, dwellings that present a higher %IOH are those built before CTE 2006 and located on top floors under the roof, with a 23.7% mean IOH, more than twice the mean %IOH of the city.

In relation to retrofitting scenarios, the actualization of buildings' envelopes to comply with the current energy regulations (*Scenario 1*) reduces IOH by an average of 8.6% and up to

15.35% in the most vulnerable typologies. Regarding the scenarios for improving the roofs of vulnerable dwellings, the scenario of retrofitting with green roof systems (*Scenario 3*) showed better results in terms of reductions in %IOH and lower temperatures by up to a 0.5 °C in comparison to the scenario of retrofitting with traditional systems and high insulation thickness (*Scenario 2*).

Beyond the above specific conclusions, the results of this study may provide some ideas and recommendations to policymakers and urban planners when rehabilitating buildings and adapting cities to climate change. In relation to the overheating diagnosis, the assessment of indoor overheating through summer with heatwaves considering the effect of the microclimate, even in temperate climates, is crucial to analyse the dwellings' performance to high temperatures, which is the expected trend in the future. In this way, the most vulnerable buildings and areas of the cities can be identified to adapt them to heatwaves and establish strategic points for regenerative and rehabilitation actions. Furthermore, energy regulations should increase the requirements regarding indoor overheating in relation to the design of dwellings and their performance, with a special focus on dwellings with only one orientation and/or located on the top floors under the roof.

Regarding the strategies to reduce overheating, this study may encourage policymakers to promote building retrofitting with nature-based solutions, considering their impact on indoor overheating and their benefits regarding the outdoor environment within cities, in order to adapt urban residential buildings and cities to warming conditions.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

IOH	Indoor Overheating Hours
AC	Air Conditioning
EU	European Union
EPBD	Energy Performance of Buildings Directive
IEA	International Energy Agency
AEMET	Spanish State Meteorological Agency, acronym in Spanish
UWG	Urban Weather Generator
UHI	Urban Heat Island
H	Average building height
SCR	Urban area building plan density (site coverage ratio)
FSR	Urban area vertical to horizontal ratio (façade to site ratio)
TCR	Fraction of the urban ground covered in trees
VCR	Fraction of the urban ground covered in grass/shrubs only
TF	Top floor
IF	Intermediate floor
NBS	Nature-Based Solution
GIS	Geographic Information System

Appendix A

Table A1. Spatial characteristics of residential typologies.

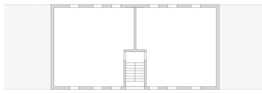
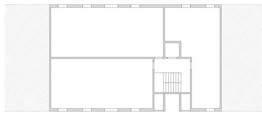
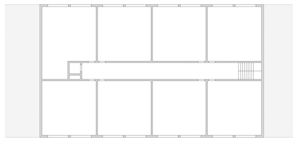
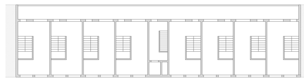
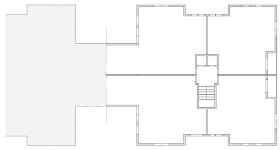
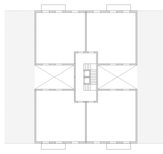
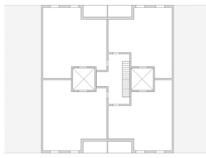
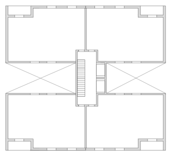
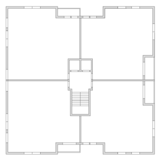
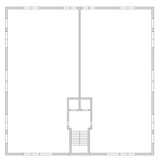
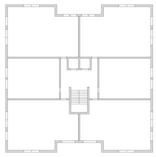
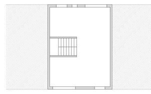
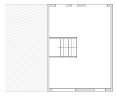
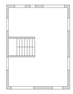
Code	Building Description	Plan
11	Linear block: 2 dwellings per floor Area of dwelling: 90 m^2 Two opposite orientations per dwelling	
12	Linear block: 3–4 dwellings per floor Area of dwelling: 85 m^2 Two dwellings with one orientation One dwelling with two opposite orientations	
13	Linear block: >8 dwellings per floor Area of dwelling: 80 m^2 Dwellings with one orientation	
14	Linear block: >8 dwellings per floor Area of dwelling (duplex): 120 m^2 Two opposite orientations per dwelling	
15	Linear block: 4 dwellings per floor Area of dwelling: 110 m^2 Two orientations per dwelling that form 90°	
21	H-block: 4 dwellings per floor Area of dwelling: 90 m^2 Two opposite orientations per dwelling	
22	H-block: 4 dwellings per floor Area of dwelling: 105 m^2 Two opposite orientations per dwelling	
31	Tower: 4 dwellings per floor Area of dwelling: 90 m^2 Two opposite orientations per dwelling	
32	Tower: 4 dwellings per floor Area of dwelling: 95 m^2 Two orientations per dwelling that form 90°	
33	Tower: 2 dwellings per floor Area of dwelling: 105 m^2 Three orientations per dwelling	

Table A1. *Cont.*

Code	Building Description	Plan
34	Tower: 6 dwellings per floor Area of dwelling: 100 m^2 Two dwellings with one orientation Four dwellings with two orientations that form 90°	
51	Detached house: Two façades Area of dwelling: 70 m^2 Two opposite orientations per dwelling	
52	Detached house: Three façades Area of dwelling: 80 m^2 Three orientations per dwelling	
53	Single house: Four façades Area: 115 m^2 Four orientations per dwelling	

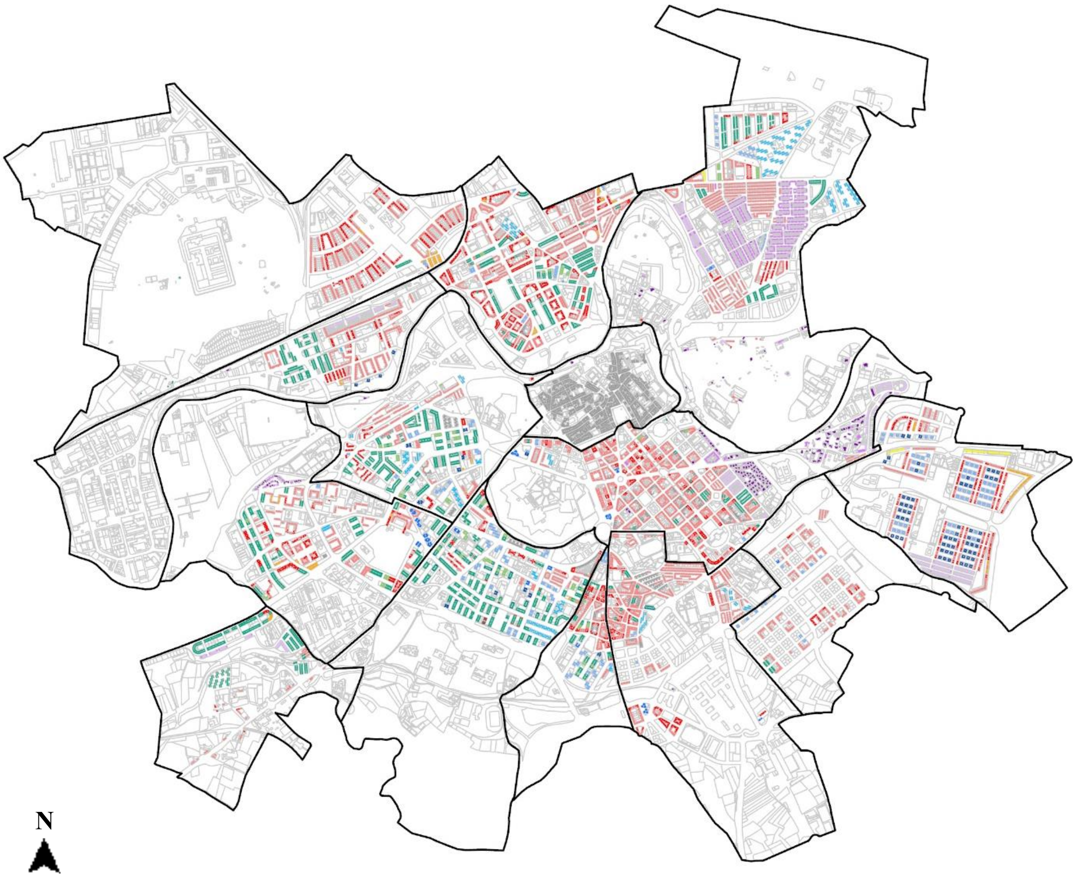


Figure A1. Residential typologies in the urban plan of Pamplona.

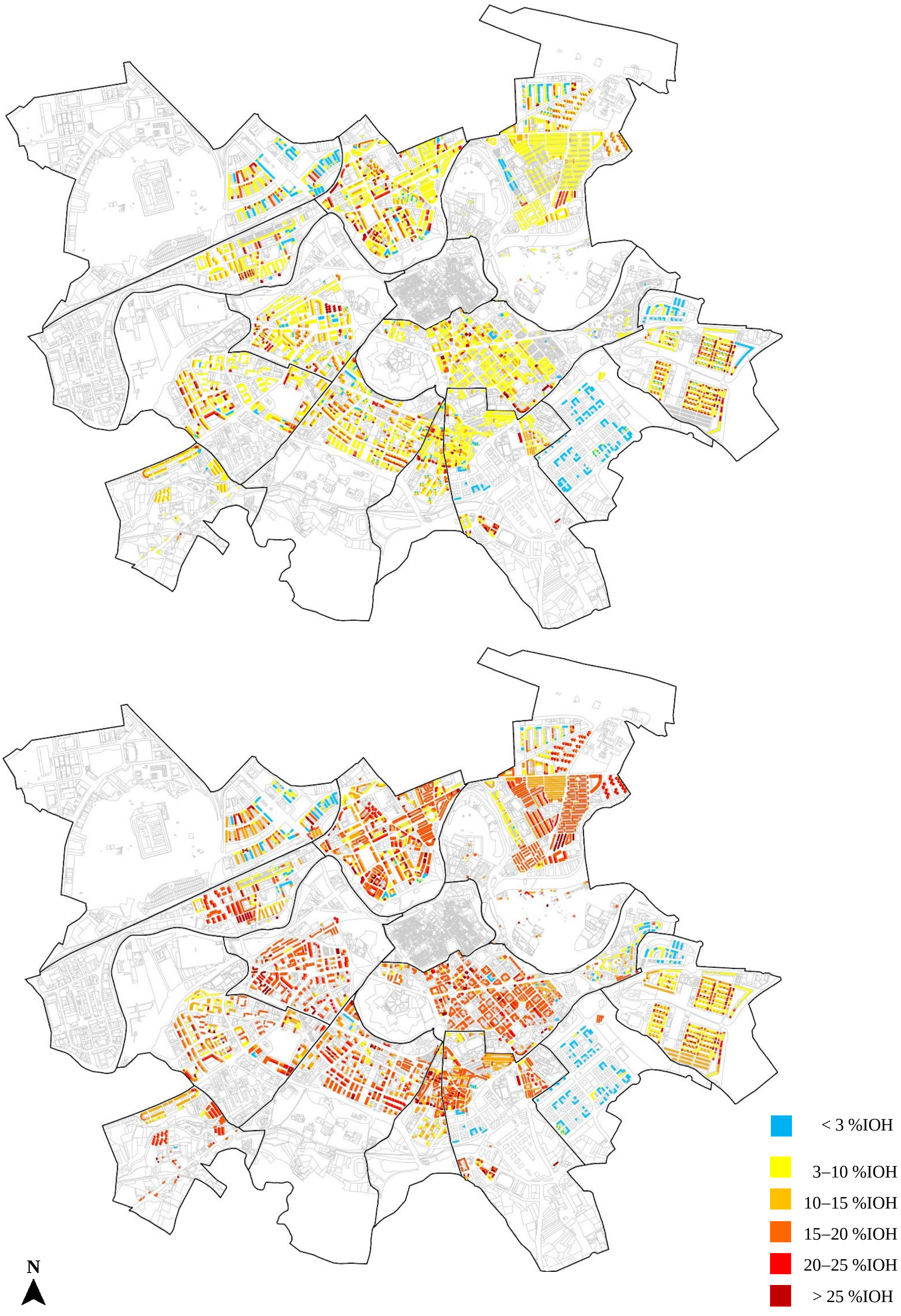


Figure A2. Results of %IOH in the current scenario (current state of residential buildings according to their built period) applied to Pamplona (Spain): intermediate floor (**top**); top floor (**bottom**).

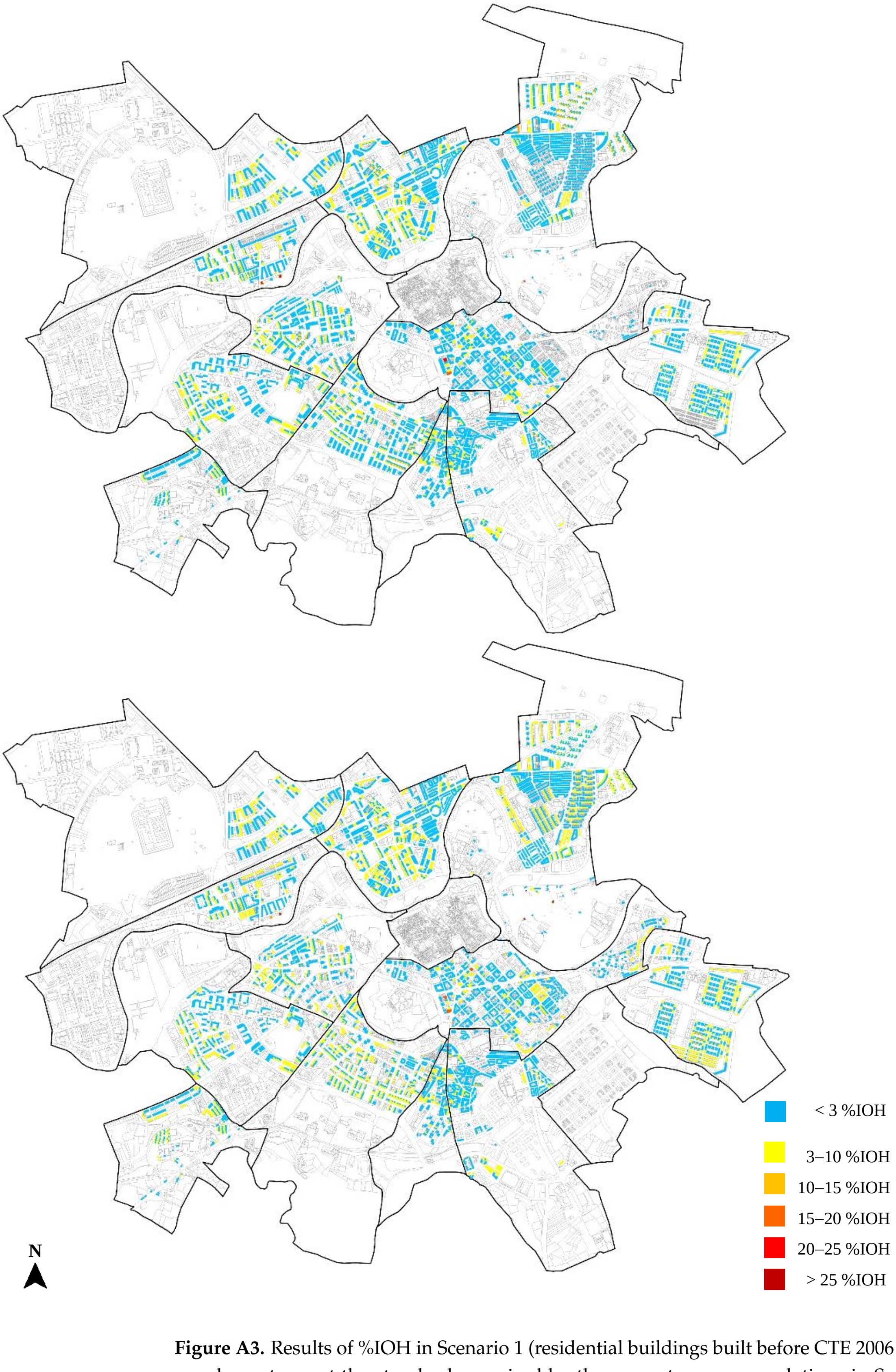


Figure A3. Results of %IOH in Scenario 1 (residential buildings built before CTE 2006 have improved envelopes to meet the standards required by the current energy regulations in Spain) applied to Pamplona (Spain): intermediate floor (**top**); top floor (**bottom**).

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