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Long-Term Analysis of Energy Consumption and Thermal Comfort in a Passivhaus Apartment in Spain

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Abstract: This study presents a detailed analysis of thermal comfort and energy consumption in a Passivhaus-certified apartment in Bolueta Tower, Bilbao, Spain, over a period of three years (2020–2022). Utilizing a comprehensive, long-term monitoring approach, the research investigates the effectiveness of the Passivhaus standard in achieving both energy efficiency and occupant comfort in a temperate climate. Using calibrated data loggers to record indoor temperature, humidity, and CO_2 levels were used alongside the collection of utility bills to assess energy consumption and thermal comfort, as well as IAQ, against several international standards. Significant issues with overheating were confirmed, in line with previous research. During the warmer months, indoor temperatures frequently exceeded the Passivhaus comfort threshold of 25 °C, reaching as high as 31.3 °C, particularly in the living room and bedroom. This resulted in discomfort during summer, with the percentage of hours above 25 °C reaching 23.21% in 2022. Nighttime temperatures often surpassed 24 °C, impacting sleep quality. Conversely, heating consumption was minimal, corroborating the building's energy efficiency in colder months. The findings highlight a critical gap in the Passivhaus standard when applied in milder climates, where overheating becomes a significant issue. This study suggests the need for an integrated approach in sustainable building design, one that balances energy efficiency with adaptive strategies to mitigate overheating, such as improved natural ventilation and thermal mass. These insights contribute to the ongoing discourse on optimizing energy-efficient buildings for occupant comfort in various climatic conditions.

Keywords: overheating; thermal comfort; energy efficiency; energy performance; nZEB; ventilation; Passivhaus; indoor environment quality (IEQ); housing; monitoring campaign; post-occupancy evaluation

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1. Introduction

There has recently been growing concern about the effects of climate change and the implications of energy consumption in buildings. In the case of Europe, the need to reduce energy consumption, exterior fuel supplies [1,2] and greenhouse gas emissions has led to legislation through regulations aimed at reducing the consumption derived from DHW production and, pre-eminently, heating typical of the predominant climate in Central and Northern Europe. Paradoxically, while legislation has been passed in this direction to try to mitigate climate change, both climate change itself—which has continued its course in recent years—and the effort made to improve energy efficiency may have contributed to undesirable effects in indoor climate in buildings, including overheating [3,4], as is generally admitted today even if an univocal relationship cannot be established [5].

Climate change will inevitably affect this, posing questions regarding housing resiliency [6] and its social implications [7]. According to an analysis by scientists at NOAA's National Centers for Environmental Information (NCEI), 2021 was the sixth-warmest year since 1880. The last 10 years (2013–2022) are among the eleven warmest years on record [8,9]. In the case of Spain, the warmest summer and autumn make 2022 the warmest year in since 1961. Eight of the ten warmest years in the 1961–2022 series belong to the 21st century [10,11]. In the case of the Basque Country, in northern Spain, thermal anomalies reached +2.0 °C [12].

Recently, a collective article about residential overheating in Europe [5] put a spotlight on this problem, with a clear definition of what overheating is in cold and temperate climates in Europe and on actions to mitigate it. Recent housing in Europe has been designed to protect against cold and retain heat rather than avoid it. This philosophy came to Europe with the advent of the European Energy Saving Directives without addressing the problem of hot summers in parallel or a perspective from the southernmost countries in Europe. In the case of the Basque Country, with a climate halfway between central Europe and the Mediterranean, the construction of buildings with an energy (heat) conservation mindset has led to an increase in overheating [4,13]. This has also occurred in the rest of Europe. Research in the near future will look at identifying the causes and look for the evidence to be able to undertake heat adaptation and mitigation measures in future buildings. As the cited article notes, a critical analysis is necessary to grasp the reasons and consequences of overheating in residential buildings located in cold and temperate regions of Europe and said analysis should involve revising how we define and measure overheating, investigating potential mitigation strategies, and considering how different policy and compliance requirements might affect the future development of housing.

In the case analysed in our work, in an attempt to follow the roadmap just described, different dwellings located in a high-performance building were monitored. Monitoring has been carried out since March 2019 in the dwelling whose results we present in this article, which includes three full years of data obtained through monitoring in 2020, 2021, and 2022. This long-term analysis makes it possible to see the evolution of the measurements obtained, to check the influence of the outside climate on the values obtained, and to assess the adaptation of the users to the dwellings. Although the case analysed is in a building constructed under the Passivhaus standard, we believe that national standards have trended towards the construction of buildings with increasingly high performance in the envelope—high compactness, insulation, and airtightness—with a similar underlying philosophy. A partial analysis of this can be found in [4].

This article also analyses energy consumption over three full years. Although this is not a measure that can be generalised to all other homes, given the infinite number of possible users, it serves as a comparison with the national average. For a house to be Passivhaus certified, it must have a total primary energy demand of less than 120 kWh per square meter per year. In other words, it must not consume more than 120 kWh/m^2 per year, including heating, cooling, domestic hot water production, appliances, lighting, and other energy consumptions. In the case of the studied building [14], the official certified values are a heating demand of 6 kWh/(m^{2}y), a heating load of 7 W/m^2 and a non-renewable primary energy demand of 98 kWh/(m^{2}y).

To contextualize said consumption, evaluating the degree of thermal comfort achieved by this house is crucial. The concept of comfort is integral to the Passivhaus standard definition, which states that a passive house is a type of building where thermal comfort, as per ISO 7730 [15], can be attained exclusively through the post-heating or post-cooling of the fresh air needed to maintain adequate indoor air quality, eliminating the necessity for extra air recirculation [16].

This means that the concept revolves around the notion that comfort within the standard ISO 7730 can mostly be achieved through the ventilation system alone. The Passivhaus approach is a development from Swedish super-insulated homes and passive solar architecture [17]. It aims to reduce the need for space heating and reduce thermal losses through the building envelope, including opaque walls, windows and doors and, additionally, mechanical ventilation with heat recovery. These advancements have led to improvements in insulation, thermal bridging, airtightness, and controlled ventilation in general practice (transference of knowledge and good practices) as well as to popularizing and boosting the commercialization of triple-glazed windows.

The Passivhaus standard defines its comfort criteria using a steady-state formula that estimates average monthly figures, excluding the impact of thermal inertia [18]. According to the Passive House Institute, the yearly duration of temperatures exceeding 25 °C should not surpass 10%. For certification, the summer comfort level must be rated "Acceptable" or higher using the Passive House Planning Package (PHPP), with less than 5% of time above 25 °C as the ideal goal, although many designers strive for no hours at all.

According to the UK Health and Safety Executive, heat stress occurs "*when the body's means of controlling its internal temperature starts to fail*" [19]. The US Center for Disease Control and Prevention lists six illnesses and conditions directly caused by heat stress [20]. Studies in female mice show that heat stroke may have a long-term impact on immune function [21]. The temperature above which heat-related stress events may occur vary, but Andrews et al. [22] suggest it can begin to occur when wet globe temperatures reach 26 °C or higher.

Heat-related mortality in Europe is higher than any other disaster-related mortality [23]. The United Kingdom Health Security Agency identified three periods of time that could be classified as heatwaves under their criteria in summer 2020 [24] and another two in the summer of 2021 [25], which ranged in duration from 3 to 11 days. The estimated total cumulative all-cause excess mortality values were estimated to be 2556 and 1634, respectively, and 87.4% and 89.9% of those deaths corresponded to people aged 65 or older. Most deaths are usually registered between June and August [26].

Research consistently shows that high nighttime temperatures in bedrooms pose a considerable health risk. Temperatures over 24 °C could disrupt sleep and lead to other health issues [27–30]. Humans spend between 20% and 40% of their time sleeping [31], and they do it primarily at home. Insufficient sleep and sleep disorders have implications in overall human performance and productivity [32,33], metabolic, cardiovascular, immunologic, and mental health; cancer; and, ultimately, general mortality [34–36]. Lack of sleep is related to an increase in inflammation, blood pressure, and higher cortisol levels [29,37]. Studies using hot chambers documented long-ago heat alters how [38–41] and how long [28,30] humans sleep. Seasons and climate are known to determine human sleeping patterns [42,43]. Building quality has a relevant effect in sleep. Wang et al. [44] found victims of natural disasters had shorter sleep after being accommodated in-to emergency housing, but the impact was less for people provided with prefabricated housing than those sleeping in relief tents. A survey-based study in the hot and humid climate of Hong Kong [27] found 60% of respondents experienced sleep disruptions related to thermal discomfort even with their air conditioners in operation. Liao et al. [45] studied the benefits of mechanical ventilation in Danish dwellings and the loss of sleep quality associated with stuffy air or excessively warm conditions. Inadequate or insufficient sleep is also related to worsened mental health in young [46–48] and older individuals [49–52].

The impact of residential architecture on thermal efficiency and contort is significant. Particularly, the relationship between occupant density and the area of usable space plays a crucial role. As the density of inhabitants increases and the usable space decreases, there is a heightened effect on the overall energy balance due to internal heat gains. This, in turn, substantially affects the indoor temperature. Notably, Spain has the highest proportion of apartment dwellers in the European Union, with 64.9% of its population living in apartments (collective housing). This is notably higher than the EU average of 46% and considerably more than countries like the United Kingdom and the Netherlands, which have less than 20% apartment dwelling populations [53].

The average house size in Spain, as recorded by the cadastre, is 144 square meters. However, this figure is somewhat misleading due to the inclusion of large, often unoccupied rural homes. A more representative figure is provided by the Basque Institute of Statistics, which reports that the average family home in the Basque Country in 2019 had a usable area of 87.2 square meters [54].

Subsidized housing tends to have lower area ratios. In the specific development under study [4,13], the average indoor usable area is approximately 76 m^2, equating to about

20.76 m^2 per person, based on an average occupancy of 3.66 occupants per dwelling as per regulations. If the statistical average of 2.38 people per household is applied, the ratio results 31.93 m^2 per person.

Regarding the occupancy of the apartment analysed in this article, it is inhabited by a single, young person that lives alone in a three-bedroom apartment of 82.42 m^2. It is to be expected in this case that internal gains due to occupancy have not significantly influenced overheating issues, as occupation density is low. It is also important to note that the occupant teleworked on a regular basis during the whole length of the study, spending many hours at home. In August 2019, the average occupancy for the entire housing development was 2.45 inhabitants per dwelling, with a ratio of 32.44 m^2 per person [13]. A new survey from the last quarter of 2023 showed an increase in total occupancy in the development, with two-person households still predominant (37.1% of respondents), followed by three-person households (25.8%) and four-person or larger households (18%).

Comparatively, in Germany and Austria, the average usable space per person is 42.9 m^2, 44 m^2 in the UK and 39.9 m^2 in France [55], while the Swiss standard SIA 2040 allocates an energy reference area of 60 m^2 per inhabitant [56]. The recent trend of younger people occupying these buildings contributes to the low occupancy values, which are expected to increase over time. This aligns well with the average usable area of dwellings in the Basque Country. The overall average occupancy rate in Spain is 2.5 inhabitants per home (2.38 in the Basque Country) [57]. However, this statistic reflects the occupancy rate of consolidated homes with diverse age profiles.

Long-term monitoring studies are relatively rare in Spain's scientific literature. Moreover, the recent adoption of Passivhaus construction standards further limits the availability of such studies. In Europe, the most extensive post-occupancy evaluation of Passivhaus dwellings comes from the EU's CEPHEUS project (Cost Effective Passive Houses as European Standards). Initiated between 1998 and 2001, it tested the technical feasibility and practicality of the Passivhaus standard across Germany, Sweden, Austria, Switzerland, and France. The project encompassed the construction of 221 homes across 14 different sites, with over 100 of these homes undergoing monitoring. While the CEPHEUS project offers a substantial dataset, it faced limitations in monitoring duration, and some heating data was extrapolated from partial-year observations. The findings revealed significant disparities in space heating consumption both across the 11 different projects and within different homes at the same location [58]. Perhaps the best-known long-term Passivhaus monitoring study is the one carried out on the first Passivhaus in Darmstadt-Kranichstein, completed in 1991 [59] and continuously monitored to some extent since then. In the period from 1991–2006, heating energy consumption averaged 9.2 kWh/m^2y [60]. According to the latest published update, in the period from 1991–2016, the average energy consumption for space heating was 8.4 kWh/m^2y [61].

In 2020, [62] reported space heating performance of a variety of Passivhaus dwellings, ranging from newly built to retrofitted homes across Germany, Austria, and the UK from 1990 to 2018. The work encompassed a diverse array of PH projects, including large-scale developments like Heidelberg's "Bahnstadt" [63], as well as smaller individual homes. It reported an average space heating energy consumption of 14.6 kWh/m^2y, significantly lower than the conventional German buildings' national average for residential buildings, which stood at 126 kWh/m^2y in the 2013–2017 period, validating the standard's effectiveness in saving heating energy. This study also found that the performance gap between calculation in the design stage and operation was low. The dwellings' geographical distribution, mainly within moderate European climates, is a limitation in terms of climatic variety in said study.

Typically, monitoring is more frequently conducted in single-family homes and over shorter periods. In Spain, there are few multi-family buildings adhering to the Passivhaus standard, though their numbers are gradually increasing. Currently, there are 60 multi-family housing developments certified as Passivhaus in Spain, for a total of 2502 apartments or units, including EnerPHit retrofits [64]. However, there is little published in the literature on their monitoring. The project in which the studied apartment is located, on the other hand, has been under continuous monitoring since the beginning of its occupancy in various apartments. This approach allows for more robust conclusions regarding the impact of external climate variations, among other factors.

Surveys are a highly effective method when addressing complex issues such as thermal discomfort. It's well-established that many comfort evaluation systems rely on user-reported perceptions that have been later turned into models. Therefore, collecting a broad range of survey responses enables us to get closer to understanding the actual comfort perception among users. Thus, utilizing surveys is recognized as the most dependable approach to identifying overheating issues in occupied buildings [65]. These surveys provide first-hand information about the occupants' comfort levels, bypassing the need for a theoretical model. Analysing the results to identify prevalent overheating complaints is crucial. Some standards state that an overheating issue can be considered to be confirmed if 20 percent or more of the occupants in any given area report experiencing overheating [66].

An extensive post-occupancy evaluation (POE) survey was designed to encompass a comprehensive perspective. It aimed not only to gauge building performance evaluation (BPE) but also to gather insights into the occupants' perceived comfort, habits, and opinions, incorporating non-technical factors in line with universal design evaluation (UDE) principles. This 28-item survey was made accessible online to all occupants of Bolueta Tower I in late summer 2019. In 2022, another survey was conducted, aimed at new residents of the new Bolueta Tower II. In 2023, a follow-up survey was executed in Bolueta Tower I, garnering over 130 individual responses.

This study aims at deriving new insights into thermal comfort, energy efficiency, and indoor air quality in high-performance buildings by presenting and analysing a large dataset, the product of an unusually extensive monitoring campaign, contributing to revealing the performance gaps, challenges to implementation of energy saving measures and practices, and to feeding the broader discourse on sustainable urban living in temperate climates. The paper is primarily organized into three sections, apart from the introduction and two appendixes with additional graphs for analysis. Section 2 describes the case study and presents the methodology we used to gather and to analyse the data. Section 3 presents the results in a detailed manner. Finally, Section 4 presents the main insights and conclusions extracted from the analysis.

2. Materials and Methods

2.1. Description of the Case Study

The apartment under study is situated in Bolueta, Bilbao, within the Basque Country, as depicted in Figure 1. Completed in 2018, the first tower [67] of this development features a 9-storey base and a 27-storey tower body. The building, known as Bolueta Tower I, comprises 171 units, with 108 being publicly protected housing (VPO) and the remaining 63 being social rental housing. The ground floor accommodates commercial spaces and other non-residential facilities. The initial group of residents moved in during March 2019. Notably, this building has achieved Passivhaus certification and is recognized as the tallest residential structure adhering to this standard to this day. Detailed descriptions of this building are available in [4,13]. Adjacent to Tower I is Tower II, a part of the same project, similar in design and construction but not subjected to Passivhaus certification [68].

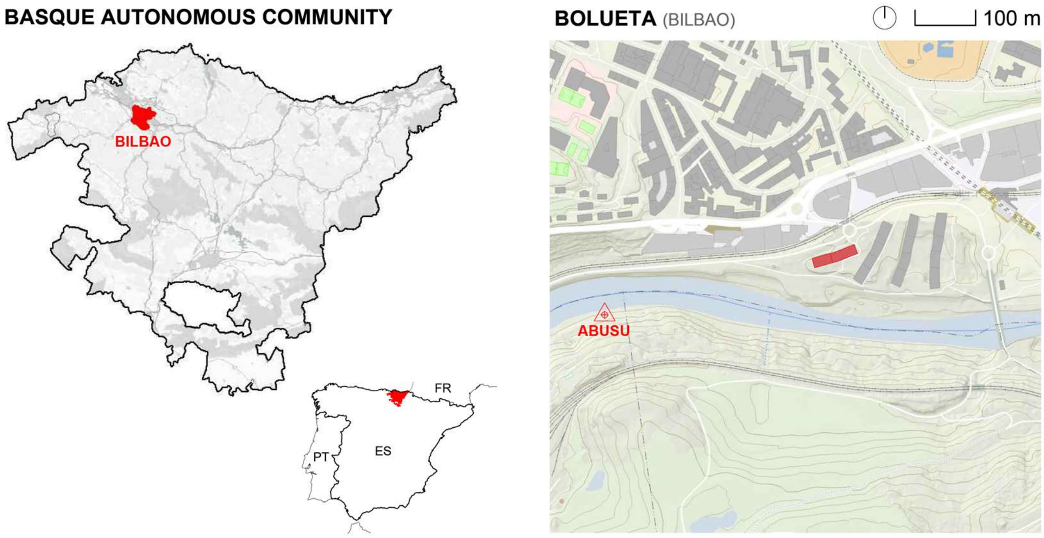

Figure 1. Location of the case study building and the Abusu meteorological station. Source: authors.

As indicated in Figure 2, the Abusu-La Peña meteorological station, located within 500 m of Bolueta Tower, was used for gathering external climate data for this study. Figure 2, in turn, offers exterior views of both Bolueta Tower I and the Abusu meteorological station. This station, part of the Euskalmet network, serves primarily as a water gauging facility.

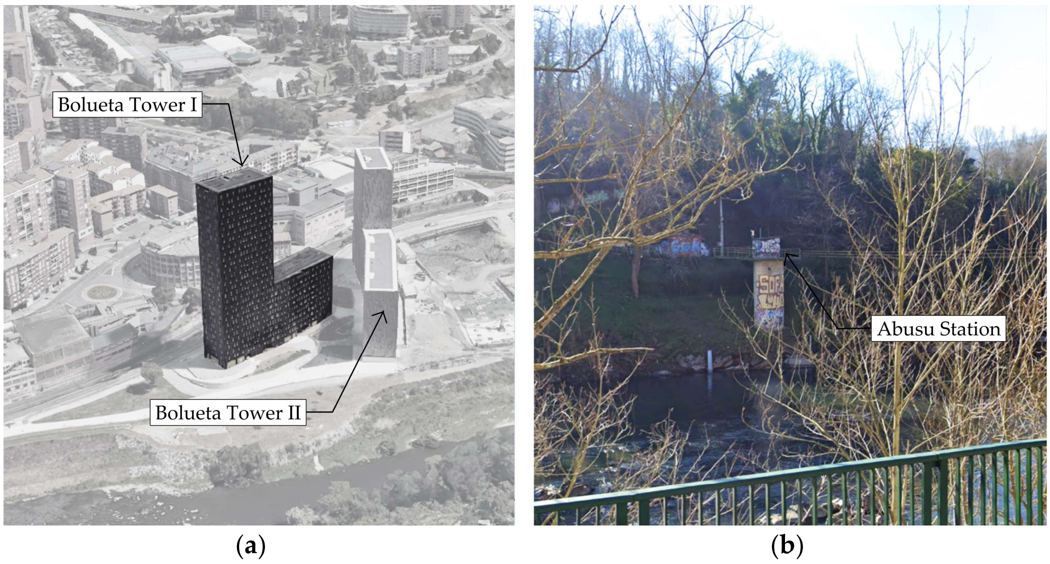

Figure 2. Exterior images of the case study. Aerial view of Bolueta Towers I (highlighted) and II (**a**) and view of the Abusu meteorological station (**b**).

The specific apartment examined for this study is on the 27th and top floor of the building. It has 82.42 square meters, three bedrooms, a kitchen, living room, bathroom, and a half-bath, along with a semi-enclosed laundry area. Its corner location allows for some limited cross-ventilation, with windows facing south and west. Table 1 summarizes key characteristics of this apartment. The glazed area calculation excludes a door to the laundry area that doesn't receive direct sunlight. If considered for other purposes, the total glazed area would be 10.37 m^2.

Table 1. Summary of characteristics of the studied dwellings.

YoC [1]	Floor Area	Interior Volume	Occupation	Orientation [2]		Glazed Area [3]	Shading System	Cross-Vent.
2018	82.42 m^2	197.89 m^3	1 adult	Two	S-W	8.46 m^2	Int. Blinds	Corner

[1] Year of construction. [2] Orientation according to CTE DB HE. [3] To calculate the glazed area, the glazed door that gives access to the laundry area was not considered, as it does not receive sunlight. If it is to be considered for other purposes, the total glazes area would amount to 10.37 m^2.

Regarding thermal characteristics of the building envelope, the thermal transmittance of the façade and roof are 0.22 and 0.21 W/m^{2}K, respectively, as gathered from [14,69]. The triple glazed windows have U-values between 0.80 and 0.85 W/m^{2}K, depending on size. The g-value of the glazing is 0.57. In the blower door airtightness test, the building performed an n_{50} value of 0.3 h^{-1}, according to the Passivhaus certificate.

2.2. Monitoring and Data Collection

For the monitoring process, commercial-grade data loggers from T&D were employed. All devices were calibrated by the manufacturer before installation. In certain instances, specifically in bedrooms, T&D Corp. (Matsumoto, Japan) RTR-576 devices equipped with three sensors (temperature, relative humidity, and CO_2 concentration) were utilized. The RTR 576's measurement range for CO_2 extends from 0 to 9999 ppm, with temperature readings from 0 to 55 °C (accuracy within ±0.5 °C) and humidity levels from 10% to 95% RH (accuracy of 5% RH at 25 °C and 50% RH). Data retrieval was facilitated through FTP transmission using T&D RTR-500 base units. A full description of the equipment can be found in [13]. All sensors were placed at an approximate height of one meter, avoiding direct sunlight and other heat sources like radiators and appliances.

Data on outdoor weather conditions was sourced from the Abusu-La Peña meteorological station, conveniently located less than 500 m from the study building. For solar radiation measurements missing in the Abusu station, another weather station located in Arrigorriaga, less than 10 km from the building under study, was utilized.

2.3. Comfort Analysis

Contemporary European standards define an indoor temperature threshold beyond which overheating is considered to occur, and a permissible excess (a limit on the number of hours this threshold can be exceeded during room occupancy periods). Overheating criteria, employing fixed temperature thresholds and excesses, vary by country and even by region within a country [70] as well as by the perceived vulnerability of the occupant groups.

Since the mid-2000s, adaptive thermal comfort criteria [71] have gained prominence. This approach proposes that in naturally ventilated buildings, individuals gradually adapt to rising or falling temperatures through changes in clothing, behaviour, and physiological adaptation. Here, the threshold temperatures linearly increase with the current average of daily mean outdoor temperatures [72] or with the monthly mean temperature [73].

In the context of sustainability, the selection of comfort models is crucial for evaluating interior climate quality, as there is no point in evaluation energy demand and consumption without measuring the associated degree of contort. The two most widely utilized models are the Thermal Balance Model—or empirical models like ISO 7730 and EN 16798, based on climatic chamber studies—and the Adaptive Models, which are grounded in field studies and take into account subjective aspects of comfort and undergo continual revision [74]. Thermal Balance Models, such as ISO 7730 [15], are best suited for indoor environments where steady-state thermal comfort or minor deviations from comfort are observed. In Spain, the current technical standard, RITE [75] is based on EN ISO 7730. Table 2 gathers the standards used to evaluate thermal comfort in this article.

Table 2. Thermal comfort standards used for this study.

Standard	Overheating Criteria
Passivhaus Institut Comfort Criteria	Limits number hours T > 25 °C Max. hours where T > 25 °C: 10%, recommends < 5%
CIBSE Guide A [66]	T_{max} 25 °C for living rooms and 23 °C for bedrooms Overheating when T > 28 °C for living rooms and T > 26 °C for bedrooms
ISO 7730 [15]	Predominantly **mechanically** ventilated buildings: - Category A: T_{min} 20 °C, T_{max} 25 °C - Category B: T_{min} 21 °C, T_{max} 25.5 °C - Category C: T_{min} 19 °C, T_{max} 27 °C RH should remain in the 40% to 60% range.
EN 16798 [72]	Predominantly **naturally** ventilated buildings: - Category I: Buildings with vulnerable occupants: T_{comf} = 0.33 Tm + 18.8 + 2 - Category II: Other buildings: T_{comf} = 0.33 Tm + 18.8 + 3 When the upper temperature limits according to the categories cannot be guaranteed by passive means, active cooling is considered unavoidable.
CIBSE TM:52 [65]	Predominantly **naturally** ventilated buildings; a room is overheated if any two of the three following criteria fail: - Criterion 1: hours of exceedance (H_e) [1] - Criterion 2: daily weighted exceedance (W_e) [2] - Criterion 3: upper limit temperature (T_{upp}) [3]
CIBSE TM:59 [76]	Predominantly **naturally** ventilated buildings: (a) Living rooms, kitchens and bedrooms: The number of hours during which ΔT is greater than or equal to 1 K during the period from May to September shall be not more than 3% of occupied hours. (b) Bedrooms only: Thermal comfort during sleeping hours requires the operating temperature in the bedroom from 23.00 to 07.00 should not exceed 26 °C for more than 1% of the annual hours. Predominantly **mechanically** ventilated buildings: (c) Living rooms, kitchens and bedrooms: Annual hours where ΔT > 1 K shall be less than 3% of occupied hours.

[1] The first criterion sets a limit for the number of hours that the operating temperature can exceed the comfort temperature threshold (upper limit of comfort) before percentage by 1 K or more during the occupied hours of a normal period outside the heating season (May to September). [2] The second criterion refers to the severity of the overheating on any given day, which is a dimensionless criterion as frequency level of which is a function of both the increase in temperature and its duration. The criteria set a daily limit for acceptability. [3] The third criterion establishes an absolute maximum daily temperature for a room, beyond which the level of overheating is unacceptable.

2.4. Energy Consumption Data

For the analysis of energy consumption, the resident provided utility bills detailing electricity, cold water, and hot water usage, along with their respective monetary costs. These bills have been consistently recorded since the initial occupation of the apartment. In this study, we will focus exclusively on the consumption data, without delving into the associated costs. Electricity bills were obtained from the energy provider, while the cold and hot water usage data were sourced from readings on the energy meters located on each floor, provided by the company responsible for the building's maintenance and energy management.

3. Results

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

3.1. Exterior Climate

The summers of 2020 [77], 2021 [78], and 2022 [78] in the Basque Country exhibited a warming trend, with 2022 being notably the second warmest summer since 2003 [78], emphasizing the urgency of climatic shifts in the region. Precipitation patterns varied, with 2020 experiencing normal to dry conditions, 2021 being generally dry except for humid conditions along the coasts, and 2022 marked by exceptional dryness, particularly in inland areas. Temperature records were consistently high across these years, with 2022's July being significant for extreme heat. The variability in rainfall did little to offset the rising temperatures, which were accompanied by increased sunlight hours in 2022, hinting at enhanced solar radiation levels according to Euskalmet's seasonal report [78].

The external climate data recorded at the local meteorological station (Abusu) for the years 2020, 2021, and 2022 is characterized in Table 3. The fundamental parameters indicate a temperate to cool climate. Nevertheless, it is observed that 2022 was the warmest year, followed by 2020, with 2021 being comparatively cooler. This pattern is consistent across both the summer and winter seasons.

Table 3. Summary of data collected in the summers 2020–2023 at Abusu weather station.

		Year	**Winter**	**Summer**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sep.**
		8760 h	**5088 h**	**3672 h**	**744 h**	**720 h**	**744 h**	**744 h**	**720 h**
Hours T > 20 °C	2020	7390	4867	2434	560	591	425	374	484
	2021	7714	4844	2788	688	565	532	513	490
	2022	7086	4699	2303	611	517	377	309	490
Hours T > 25 °C	2020	299	3	296	60	32	51	87	66
	2021	158	14	144	11	27	26	25	55
	2022	412	32	380	39	53	115	100	73
% Hours T > 25 °C	2020	3.4	0.1	8.1	8.1	4.4	6.9	11.7	9.2
	2021	1.8	0.3	3.9	1.5	3.8	3.5	3.4	7.6
	2022	4.7	0.6	10.3	5.2	7.4	15.5	13.4	10.1
Hours > T 28 °C	2020	88	0	88	19	7	12	29	21
	2021	48	0	48	5	9	6	0	28
	2022	190	0	190	13	30	71	40	36
Max. T	2020	38.7	25.8	38.7	31.4	32.1	38.7	38.2	35.6
	2021	35.3	27.0	35.3	35.3	35.3	35.3	35.3	35.3
	2022	39.4	27.1	39.4	32.1	38.1	39.4	36.8	37.0
Hours RH > 70%	2020	6060	3687	2293	466	493	457	513	365
	2021	5766	3199	2543	440	514	535	526	528
	2022	5467	3164	2283	460	515	402	494	412
% Hours RH > 70%	2020	69.2	42.1	62.5	62.7	68.6	61.5	69.0	50.8
	2021	65.8	36.5	69.3	59.2	71.5	72.0	70.8	73.4
	2022	62.4	36.1	62.2	61.9	71.6	54.1	66.5	57.3
Max. RH	2020	98.2	98.2	96.3	96.3	96.2	96.2	96.3	96.2
	2021	97.2	96.2	97.2	96.2	96.6	96.3	96.4	97.2
	2022	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3

Appendix A presents the temperature/relative humidity pairs for the summer months (May to September) of the years 2020, 2021, and 2022. A noteworthy measurement is the number of hours exceeding 25 °C during the summer, which was 3.9% in 2021, 8.1% in 2020, and 10.3% in 2022.

Another method to assess climate severity regarding heat is presented in Table 4, which displays the solar radiation values at the Arrigorriaga meteorological station, located approximately 10 km from the studied residence. Here, we note that the years 2020 and 2022 experienced higher annual radiation levels, though the differences are not markedly distinct. However, these findings deviate from the design manuals, namely the *National*

Solar Radiation Atlas 2003–2005 [79] and the *Basque Country Solar Radiation Atlas* [80]. The data provided are generated by the Meteonorm v8 software [81] for the location of the building. This program indicates significantly high variables based on the data used for its generation.

Table 4. Summary of radiation data collected at the Arrigorriaga weather station.

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
							kWh/m^{2}Day						**kWh/m^{2}y**
2019	1.53	3.39	5.15	5.26	7.16	7.41	7.04	6.50	5.18	3.43	1.52	1.73	1684
2020	2.05	2.92	4.29	5.05	7.44	6.56	7.49	6.27	5.51	2.81	2.47	1.38	1652
2021	1.55	2.26	4.27	5.53	6.65	6.33	6.44	6.12	4.48	3.83	1.67	1.74	1552
2022	2.32	2.81	3.71	5.20	7.16	6.50	7.53	6.34	5.00	3.35	1.95	1.41	1624
Avg.	1.86	2.84	4.35	5.26	7.10	6.70	7.13	6.31	5.05	3.35	1.90	1.57	1628
AEMET Solar Radiation Atlas 2003–2005 [79]													
	1.56	2.23	3.43	4.30	5.17	5.55	5.49	4.87	4.08	2.72	1.70	1.38	1294
EVE Solar Radiation Atlas of the Basque Country [80]													
	1.33	1.99	2.85	3.88	4.71	5.10	5.09	4.59	3.59	2.50	1.62	1.11	1169
Bolueta data by interpolation using Meteonorm 2000–2009 (Temperature) 1981–1990 (Radiation)													
	1.90	3.04	4.52	6.30	6.71	7.77	7.42	6.10	5.50	3.61	2.30	1.68	1731
Bolueta data by interpolation using Meteonorm 2000–2009 (Temperature) 1991–2010 (Radiation)													
	1.35	2.11	3.32	4.23	5.06	5.47	5.35	4.68	3.80	2.58	1.53	1.13	1238

3.2. Comfort Analysis

3.2.1. Temperature, Relative Humidity, and CO_2 Concentration Analysis

The tabulated temperature data for the living room and the main bedroom are presented below (Table 5). Regarding temperatures, it has been observed that in the living room, the maximum temperatures during the three years of monitoring were reached in August and September, exceeding 29 °C and recording a peak of 31.3 °C in September 2022. The bedroom displayed similar readings; however, considering that any temperature above 24 °C can disrupt sleep, elevated measurements during the night hours were noted, necessitating further analysis.

Table 5. Summary of recorded indoor air temperature data.

							Living Room							
		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Overall
2020	**Avg. T** (°C)	23.32	22.52	21.49	22.77	23.94	23.85	25.54	25.77	25.16	22.10	22.59	21.51	**23.22**
	Min. T (°C)	19.40	19.80	19.50	19.50	19.20	20.00	22.70	20.40	17.50	20.40	15.20	19.00	**15.20**
	Max. T (°C)	24.10	24.60	24.00	24.90	27.10	26.90	28.10	29.00	29.40	25.80	25.90	24.10	**29.40**
2021	**Avg. T** (°C)	21.09	21.99	22.28	22.91	22.94	24.04	24.76	24.47	25.18	24.63	21.63	21.30	**23.11**
	Min. T (°C)	19.10	20.70	20.50	19.80	20.20	20.00	20.70	21.70	20.40	22.00	19.50	19.20	**19.10**
	Max. T (°C)	23.10	27.70	27.00	25.40	25.00	27.40	27.10	27.20	29.40	27.40	25.20	24.90	**29.40**
2022	**Avg. T** (°C)	21.55	21.23	21.54	21.67	23.28	24.10	25.33	25.63	25.28				**23.31** [1]
	Min. T (°C)	19.60	19.80	19.70	19.70	17.60	17.60	19.20	19.10	19.90				**17.60**
	Max. T (°C)	25.10	24.20	25.40	24.70	26.10	27.90	29.80	29.10	31.30				**31.30**
							Bedroom							
		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Total
2020	**Avg. T** (°C)							26.80 [2]	26.24	25.76	23.44	24.25	22.29	**24.62** [2]
	Min. T (°C)							24.30 [2]	19.30	19.80	19.80	22.00	20.50	**19.30**
	Max. T (°C)							28.30 [2]	28.30	28.50	29.40	25.60	26.50	**29.40**
2021	**Avg. T** (°C)	22.07	22.64	22.86	23.35	23.32	24.42	25.31	25.31	25.69	25.75	23.42	22.95	**23.93**
	Min. T (°C)	20.70	21.20	21.70	20.70	22.00	19.70	22.10	20.30	16.70	22.00	21.60	20.60	**16.70**
	Max. T (°C)	23.80	25.10	25.40	25.30	24.90	26.90	27.20	27.70	28.80	28.70	26.20	25.90	**28.80**
2022	**Avg. T** (°C)	23.07	23.11	23.21	24.51	25.19	26.52	26.65	26.04	25.28				**24.85** [1]
	Min. T (°C)	21.60	21.50	21.40	21.10	19.50	20.60	21.10	20.10	19.90				**19.50**
	Max. T (°C)	24.70	24.90	25.20	26.80	28.10	30.40	29.60	29.30	31.30				**31.30**

[1] Incomplete period. Monitoring ends 30 September 2020. [2] Incomplete period. Monitoring begins 15 July 2020.

As for relative humidity (Table 6), the values remained relatively low, which is notable given the climatic zone where the building is situated. These low humidity levels can be attributed to the high indoor temperatures and consistent ventilation. The highest relative humidity was found in July and August, with a peak of 88%, coinciding with the months when natural ventilation is most prevalent.

Table 6. Summary of recorded indoor Relative Humidity.

		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Overall
Living Room														
2020	**Avg. RH** (%)	43.6	46.4	47.7	51.2	54.0	56.0	57.9	60.0	53.9	55.1	49.5	48.4	**52.0**
	Min. RH (%)	39.0	41.0	40.0	36.0	48.0	46.0	50.0	45.0	40.0	47.0	42.0	42.0	**36.0**
	Max. RH (%)	50.0	53.0	57.0	59.0	64.0	66.0	71.0	77.0	67.0	64.0	67.0	56.0	**77.0**
2021	**Avg. RH** (%)	47.0	47.6	44.8	43.1	49.7	58.6	59.6	61.2	60.0	49.9	50.7	50.2	**51.9**
	Min. RH (%)	39.0	40.0	35.0	32.0	44.0	52.0	53.0	51.0	51.0	41.0	44.0	40.0	**32.0**
	Max. RH (%)	60.0	54.0	52.0	52.0	59.0	68.0	77.0	77.0	84.0	59.0	57.0	59.0	**84.0**
2022	**Avg. RH** (%)	43.6	46.4	46.0	48.2	54.8	60.7	59.6	63.4	54.8				**53.1** [1]
	Min. RH (%)	38.0	41.0	40.0	41.0	49.0	50.0	51.0	54.0	41.0				**38.0**
	Max. RH (%)	56.0	53.0	51.0	57.0	69.0	73.0	88.0	76.0	79.0				**79.0**
Bedroom														
		Jan.	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**	**Total**
2020	**Avg. RH** (%)							55.5 [2]	56.7	49.5	51.3	43.8	43.8	**49.6** [2]
	Min. RH (%)							48.0 [2]	37.0	28.0	39.0	33.0	35.0	**28.0**
	Max. RH (%)							65.0 [2]	78.0	66.0	66.0	57.0	58.0	**78.0**
2021	**Avg. RH** (%)	42.4	43.2	40.3	38.0	45.8	55.2	55.5	56.0	55.4	43.2	42.6	42.6	**46.7**
	Min. RH (%)	31.0	33.0	25.0	18.0	36.0	41.0	46.0	45.0	44.0	33.0	33.0	28.0	**18.0**
	Max. RH (%)	60.0	56.0	51.0	50.0	60.0	74.0	67.0	69.0	76.0	55.0	53.0	53.0	**76.0**
2022	**Avg. RH** (%)	37.8	37.6	40.0	47.7	54.1	52.9	57.1	47.2	54.8				**47.8** [1]
	Min. RH (%)	30.0	31.0	31.0	41.0	43.0	42.0	47.0	37.0	41.0				**30.0**
	Max. RH (%)	79.0	53.0	51.0	57.0	69.0	73.0	88.0	76.0	79.0				**88.0**

[1] Incomplete period. Monitoring ends 30 September 2020. [2] Incomplete period. Monitoring begins 15 July 2020.

CO_2 levels, as shown in Table 7, were generally low on average, with occasional spikes observed. Specifically, in the bedroom, the winter months from November to February exhibited higher CO_2 values.

Table 7. Summary of the registered CO_2 concentration, in ppm.

		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Overall
Living Room														
2020	**Avg. [CO_2]** (ppm)	530	510	522	563	580	539	505	532	538	580	2072	566	**668**
	Min. [CO_2] (ppm)	398	315	398	415	398	386	413	367	371	448	434	394	**315**
	Max. [CO_2] (ppm)	1076	774	779	778	834	766	664	744	762	913	5014	1122	**5014**
2021	**Avg. [CO_2]** (ppm)	574	532	558	540	542	554	541	514	540	508	574	547	**544**
	Min. [CO_2] (ppm)	413	389	398	407	407	415	418	411	373	414	410	398	**373**
	Max. [CO_2] (ppm)	1097	691	845	767	736	870	683	702	711	655	1290	742	**1290**
2022	**Avg. [CO_2]** (ppm)	536	529	526	520	507	527	549	543	561				**533** [1]
	Min. [CO_2] (ppm)	402	400	412	395	387	389	416	381	432				**381**
	Max. [CO_2] (ppm)	1152	718	770	644	674	758	780	794	834				**1152**
Bedroom														
		Jan.	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**	**Overall**
2020	**Avg. [CO_2]** (ppm)							496 [2]	485	509	734	672	719	**611** [2]
	Min. [CO_2] (ppm)							388 [2]	375	389	388	399	381	**375**
	Max. [CO_2] (ppm)							706 [2]	698	1207	2001	1457	1501	**2001**
2021	**Avg. [CO_2]** (ppm)	751	672	723	585	639	534	523	491	505	517	665	659	**605**
	Min. [CO_2] (ppm)	374	366	378	369	387	385	389	386	393	384	388	377	**366**
	Max. [CO_2] (ppm)	1552	691	845	767	736	870	683	702	711	655	1290	742	**1552**
2022	**Avg. [CO_2]** (ppm)	604	594	548	525	483	472	476	458	561				**524** [1]
	Min. [CO_2] (ppm)	380	380	392	392	389	384	393	386	432				**380**
	Max. [CO_2] (ppm)	1152	718	770	644	674	758	780	794	834				**1152**

[1] Incomplete period. Monitoring ends 30 September 2020. [2] Incomplete period. Monitoring begins 15 July 2020.

3.2.2. Thermal Comfort Evaluation

The analysis that follows examines the levels of comfort achieved according to the various standards mentioned. Annex 1 contains comfort graphs for the living room and bedroom for the years 2020, 2021, and 2022 based on the EN ISO 7730 [15] and EN 16798 [72] standards.

Passivhaus Institut Criteria

Firstly, considering the criteria set by the Passivhaus Institut, the primary parameters include the number of hours with temperatures exceeding 25 °C and the hours with absolute humidity above 12 g/kg. The results of this compliance analysis are shown in Table 8. It was observed that none of the years under review achieved comfort levels suitable for certification. Both the living room and the bedroom significantly exceeded the 15% threshold of hours above 25 °C, which is deemed catastrophic by the Passivhaus Institut. This issue is particularly pronounced in the bedroom, which has only one south-facing window, hindering proper ventilation and remaining closed for more extended periods during the night. In the original certification process, the building was granted certification with a theoretical value of 7% of hours exceeding 25 °C. In comparison, Table 8 presents the analysis of the actual collected data.

Table 8. Thermal comfort assessment according to the Passivhaus temperature requirements.

				Living Room				
Year	**Total Year Hours**	**Analysed Hours**	**HoursT > 25 °C**	**% Hours T > 25 °C (Analysis)**	**% Hours T > 25 °C (Year)**	**Yearly Limit**	**Assessment [2]**	
2020 [1]	8760 h	8760 h	1790 h	20.43%	20.43%	876 h (10%)	*"Catastrophic"*	•
2021		8760 h	1181 h	13.48%	13.48%		*"Poor"*	•
2022		6582 h	1528 h	23.21%	17.44%		*"Catastrophic"*	•
				Bedroom				
Year	**Total year hours**	**Analysed hours**	**HoursT > 25 °C**	**% Hours T > 25 °C (analysis)**	**% Hours T > 25 °C (year)**	**Yearly limit**	**Assessment**	
2020 [1]	8760 h	4064 h	1645 h	40.48%	18.78%	876 h (10%)	*"Catastrophic"*	•
2021		8760 h	2270 h	25.91%	25.91%		*"Catastrophic"*	•
2022		6552 h	2786 h	42.52%	31.80%		*"Catastrophic"*	•

[1] The additional hours of the leap year are not considered. [2] Assessment as per the Passivhaus Institut overheating criteria, where less than 2% is considered *"Excellent"*; 2–5%, *"Good"*; 5–10%, *"Acceptable"*; 10–15%, *"Poor"* and over 15%, *"Catastrophic"*. The color of the dots indicates the degree of passing/failure.

Table 9 allows us to analyse the monthly distribution of such periods of exceedance, which are classified as "poor" or "catastrophic" if the whole year is considered. It can be seen that although most of the hours with temperature over 25 °C are concentrated during the summer months, there are also some events throughout the year, and a very considerable share of hours of exceedance of said threshold during May and October.

Table 9. Monthly share of time where interior T > 25 °C.

						Living Room							
Year	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**	**Total [1]**
2020	-	-	-	-	19.49%	19.03%	69.76%	74.06%	56.94%	0.27%	3.61%	-	**20.43%**
2021	-	0.60%	1.48%	0.83%	-	18.61%	35.89%	24.87%	46.94%	31.32%	0.42%	-	**13.48%**
2022	0.27%	0.00%	0.27%	0.00%	6.72%	26.67%	52.82%	68.55%	52.64%				**17.44%**
						Bedroom							
Year	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**	**Total [1]**
2020							52.15%	83.20%	70.28%	2.28%	15.97%	-	**18.78%**
2021	-	0.15%	0.94%	0.69%	-	25.00%	64.38%	64.92%	68.89%	77.69%	4.31%	1.34%	**25.91%**
2022	-	-	1.48%	30.42%	60.22%	81.53%	88.98%	64.52%	52.64%				**31.80%**

[1] Over 8760 h.

The risk of overheating in cold and temperate climates is primarily influenced by external air temperature and solar radiation, with humidity and wind speed also playing contributory roles. The Passivhaus Institut sets maximum parameters for absolute humidity which, in this instance, are well within the compliant range. Other comfort models consider the combined effect of temperature and relative humidity, such as those outlined in EN ISO 7730, detailed in Appendix A. Table 10 presents the data for absolute humidity compliance according to the Passivhaus Institut.

Table 10. Absolute humidity assessment according to the Passivhaus standard.

Living Room								
Year	**Total Year Hours**	**Analysed Hours**	**Hours W > 12 g/kg**	**% Hours W > 12 g/kg (Analysis)**	**% Hours W > 12 g/kg (Year)**	**Yearly Limit**	**Assessment [2]**	
2020 [1]	8760 h	8760 h	1065 h	12.16%	12.16%	1752 h (20%)	Pass	●
2021		8760 h	1074 h	12.26%	12.26%		Pass	●
2022		6582 h	1405 h	21.35%	16.04%		Pass	●
Bedroom								
Year	**Total year hours**	**Analysed hours**	**Hours W > 12 g/kg**	**% Hours W > 12 g/kg (analysis)**	**% Hours W > 12 g/kg (year)**	**Yearly limit**	**Assessment**	
2020 [1]	8760 h	4064 h	726 h	17.86%	8.29%	1752 h (20%)	Pass	●
2021		8760 h	735 h	8.39%	8.39%		Pass	●
2022		6552 h	1173 h	17.90%	13.39%		Pass	●

[1] The additional hours of the leap year are not considered. [2] Assessment as per the Passivhaus Institut absolute humidity criterion. The color of the dots indicates the degree of passing/failure.

CIBSE TM59 and EN 16798

The CIBSE TM59 makes a distinction between mechanically ventilated and naturally ventilated buildings. The apartment in question is equipped with a ventilation system that ensures a minimum airflow around the clock, which can be increased to two other levels. However, this mechanical ventilation system does not have the capacity to move air volumes that would significantly impact the cooling of the dwelling. Designed for a total supply airflow of 160 m^3/h, in situ measurements indicate that the maximum speed setting only achieves a flow rate of approximately 72 m^3/h. In general, we rely on survey responses regarding the number of hours windows are kept open. In the studied case, the occupant opens the windows whenever an excess of heat is felt and engages in nighttime over-ventilation. The performance according to the two models proposed by CIBSE TM59 will be analysed in the following tables, the first one being Table 11.

When analysed as a predominantly naturally ventilated building, it is the bedroom that faces greater challenges in meeting comfort parameters. In other words, the adaptive analysis appears optimistic regarding the dwelling's comfort; however, the quantitative analysis of nighttime hours above 26 °C falls short of the required standards.

Table 11. Compliance of the criteria of CIBSE TM59 [76] for predominantly naturally ventilated dwellings.

2020												
Room	**Analysed Hours**	**Cat.**	**Hours of Exceedance, H_e [1]**				**Night Hours T > 26 °C [2]**				**Overheating [3]**	
			Hours	**%**	**Limit**		**Hours**	**%**	**Limit**			
Living room	8760 h	I	30 h	0.34%	3%	●					No	●
		II	0 h	0.00%		●					No	●
Bedroom	4064 h	I	50 h	0.57%	3%	●	365 h	11.1%	1%	●	Yes	●
		II	6 h	0.07%		●						

Table 11. *Cont.*

2021												
Room	**Analysed hours**	**Cat.**	**Hours of Exceedance, H_e [1]**				**Night Hours T > 26 °C [2]**				**Overheating**	
			Hours	**%**	**Limit**		**Hours**	**%**	**Limit**			
Living room	8760 h	I	2 h	0.02%	3%	●					No	●
		II	0 h	0.00%		●					No	●
Bedroom	8760 h	I	1 h	0.01%	3%	●	181 h	5.51%	1%	●	Yes	●
		II	0 h	0.00%		●						
2022												
Room	**Analysed hours**	**Cat.**	**Hours of Exceedance, H_e [1]**				**Night Hours T > 26 °C [2]**				**Overheating**	
			Hours	**%**	**Limit**		**Hours**	**%**	**Limit**			
Living room	6582 h	I	12 h	0.14%	3%	●					No	●
		II	4 h	0.05%		●					No	●
Bedroom	6552 h	I	323 h	3.69%	3%	●	572 h	17.41%	1%	●	Yes	●
		II	46 h	0.53%		●						

[1] Hours of exceedance (May–September) must not exceed 3%. [2] Number of annual nighttime hours (22:00–07:00 h) in which T > 26 °C must not exceed 1% (bedrooms only). [3] Overheating exists if either criterion is failed. The color of the dots indicates the degree of passing/failure.

In the analysis as a predominantly mechanically ventilated building (Table 12), which assesses a model based on exceeding temperature thresholds, it is observed that in none of the three years analysed did the building remain within comfortable temperature ranges, experiencing more intense overheating episodes in 2022 and 2020. The year 2021 displayed significantly lower values, yet it still failed to meet the set limits at any point. The bedroom, in particular, exhibited more pronounced overheating compared to the rest of the dwelling.

Table 12. Compliance of the criteria of CIBSE TM59 [76] for predominantly mechanically ventilated dwellings, or percentage of hours with T > 26 °C.

Living Room															
Year	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**	**Total**	**Overheating [1]**	
2020	-	-	-	-	5.24%	6.53%	30.78%	46.10%	32.50%	-	-	-	10.18%	Yes	●
2021	-	-	-	-	5.24%	6.53%	30.78%	46.10%	32.50%	-	-	-	4.77%	Yes	●
2022	-	-	-	-	0.13%	7.50%	35.62%	40.46%	37.92%				10.21%	Yes	●
Bedroom															
Year	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**	**Total**	**Overheating [1]**	
2020							42.61%	63.84%	45.56%	-	-	-	12.91%	Yes	●
2021	-	-	-	-	-	2.78%	13.17%	17.61%	36.25%	34.68%	0.69%	-	8.82%	Yes	●
2022	-	-	-	3.33%	25.94%	58.47%	72.85%	49.19%	37.92%				20.76%	Yes	●

[1] Overheating exists if the temperature is higher than 26 °C for more than 3% of annual occupied hours or 263 h. The color of the dots indicates the degree of passing/failure.

CIBSE Guide A

CIBSE's Guide A: Environmental design [66] provides guidance on sleep quality, highlighting that temperatures above 24 °C may impair sleep and recommending that peak bedroom temperatures should not surpass 26 °C. Table 13 enumerates the significant number of nocturnal hours (22:00 to 07:00) during which the bedroom temperature exceeds 24 °C. The highest incidence was recorded in 2022, with 44% of the annual hours exceeding this threshold, and with the months of June and July witnessing nearly all hours above 24 °C.

Table 13. Percentage of nighttime hours (22:00–07:00 h) where T > 24 °C, the temperature at which quality of sleep begins to decrease according to CIBSE Guide A [66,82].

Living Room													
Year	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**	**Total [1]**
2020	-	-	-	6.67%	49.82%	38.52%	92.83%	85.30%	74.81%	0.72%	10.00%	0.00%	30.11%
2021	-	-	2.38%	11.11%	5.73%	45.93%	72.76%	51.61%	81.48%	75.27%	-	-	29.01%
2022	2.15%	-	-	0.37%	15.77%	38.89%	70.97%	80.29%	60.37%				22.56%
Bedroom													
Year	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**	**Total [1]**
2020							52.33%	89.96%	78.89%	8.60%	47.04%	-	23.17%
2021	-	-	1.98%	14.81%	10.75%	77.04%	96.77%	91.40%	92.59%	91.76%	17.41%	7.17%	42.04%
2022	4.30%	12.30%	17.46%	67.78%	85.30%	95.56%	94.98%	81.36%	60.37%				43.26%

[1] Over total yearly nighttime hours (22:00–07:00 h).

Appendix B shows the comfort graphs according to EN 7730 and EN 16798. The following table (Table 14) reports the results of CO_2 measurements in the dwelling and the level of compliance with Spanish regulations. Mechanical ventilation ensures optimal air quality throughout the year. In addition to this, frequent hourly renewals are carried out during the summer in an attempt to evacuate the indoor heat.

Table 14. Indoor air quality assessment according to CTE DB-HS 3 [82].

	Living Room						Bedroom					
Year	**Average [CO_2]**	**Limit**	**Assessment**	**Excess [1] (ppm·h)**	**Limit (ppm·h)**	**Assessment**	**Average [CO_2]**	**Limit**	**Assessment**	**Excess [1] (ppm·h)**	**Limit (ppm·h)**	**Assessment**
2020	668 ppm	900 ppm	Pass •	652,531	500,000	Fail •	668 ppm	900 ppm	Pass •	821	500,000	Pass •
2021	544 ppm	900 ppm	Pass •	0	500,000	Pass •	544 ppm	900 ppm	Pass •	0	500,000	Pass •
2022	533 ppm	900 ppm	Pass •	0	500,000	Pass •	533 ppm	900 ppm	Pass •	0	500,000	Pass •

[1] Annual cumulative sum of ppm·h over 1600 ppm.

3.2.3. Survey Insights

Three survey campaigns have been conducted among residents over the past few years, as explained in Section 1. In the case of the case study apartment, interviews with the occupant reflected findings consistent with the general survey responses. We will now detail the most critical aspects related to comfort from the two surveys conducted in October 2020 and October 2023. The collected responses corroborate the monitoring results. However, residents generally express satisfaction with the housing design, indicating that comfort-related responses do not reflect dissatisfaction with other aspects of the building's design. For the occupant of the analysed dwelling, the survey responses are in line with the majority, noting complaints of excessive heat both day and night, as presented in Table 15.

Table 15. Selected insights from the 2020 and 2024 surveys.

Question	**October 2020 (84 Respondents)**		**October 2023 (134 Respondents)**	
What is your usual thermal sensation in the winter inside your home?	Neutral Slightly warm Warm Very warm	66.7% 11.9% 14.3% 0.5%	Neutral Slightly warm Warm Very warm	64.4% 12.2% 11.1% 4.4%
In winter, do you have difficulty sleeping due to discomfort in your home?	No Yes, due to heat	72.7% 18.2%	No Yes, due to heat	74.4% 14.4%
What is your usual thermal sensation in the summer inside your home? *	Slightly warm Warm	2.4% 97.6%	Slightly warm Warm Very warm	8.9% 27.8% 60.0%
In summer, do you have difficulty sleeping due to discomfort in your home?	Yes, due to heat No	97.0% 3.0%	Yes, due to heat No	81.1% 18.9%

Table 15. *Cont.*

Question	October 2020 (84 Respondents)		October 2023 (134 Respondents)	
Rate from 1 to 10 the overall quality of your dwelling.	<5, 5–6, 7–8, 9–10	19.1% 39.2% 35.7% 6.0%	<5, 5–6, 7–8, 9–10	15.5% 18.9% 62.2% 3.3%

* This question was modified in the 2023 survey to achieve a better degree of granularity.

3.3. Energy Consumption Analysis

The various utility consumptions compiled from the user-provided invoices are detailed here. These invoices comprehensively show the readings of the cold water meters and the energy consumption for hot water. Since 19 March 2019, when the apartment became occupied, complete records of water and energy consumption are available. A single invoice encompasses both cold water usage and the energy reading in kWh for hot water. Due to irregular billing periods, the following tables present a complete one-year period from July 2021 to July 2022 and the total consumption since the start of occupancy on 10 March 2019 until the end of 2022.

3.3.1. Cold Water Consumption

The average daily water consumption is about 125 L. According to the INE (National Statistics Institute) Water Supply and Sanitation Statistics of 2020, the average daily consumption per person in Spain is 133 L, similar to the 2018 figure. For the Basque Country, this statistic indicates a lower value, with the region having the lowest household water consumption in Spain, at 104 L per person per day. The household consumption of cold water, as seen in Table 16, falls within the average range for the area.

Table 16. Cold water consumption from the start of monitoring (19 March 2019, to 19 January 2023).

Period	Start Date	End Date	Number of Days	m^3	L/Day
Year	20/07/2021	20/07/2022	365	47	128.8
Total	10/03/2019	19/01/2023	1441	165	116.9

3.3.2. Domestic Hot Water and Heating Consumption

Regarding energy consumption for heating and domestic hot water (DHW), the invoices do not separate these two utilities. Tables 17 and 18 present the total consumption for both, applying a normative approximation based on the number of occupants and the cold water temperature, as per the methodology of the Technical Building Code DB HE. The occupant rarely uses the heating system, primarily to check its functioning rather than for comfort needs, aligning with survey responses from many apartments in the building. In a survey conducted two years after first occupation, 16.7% responded that they never turn on the heating, and 40.5% only occasionally. In the 2023 survey, 33.3% reported never using the heating, and 43.3% only on very cold winter days. This suggests that the energy consumption from the meter is almost exclusively due to DHW production.

Table 17. Energy consumption (DHW and heating) from the start of monitoring (19 March 2019, to 19 January 2023).

						DHW (Normative)		Heating	
	Start Date	End Date	No. of Days	kWh/Year	kWh/Day	kWh/Year	kWh/Day	kWh/Year	Heating kWh/Day
Year	20/07/2021	20/07/2022	365	732	2.01	590	1.62	142	0.39
Total	10/03/2019	19/01/2023	1441	165	1.95	590	1.62	142	0.33

Table 18. Energy consumption (DHW and heating) from the start of monitoring (19 March 2019, to 19 January 2023) per useful surface area.

				Total		DHW (Normative)		Heating	
	Start Date	**End Date**	**No. of Days**	**W/m²y**	**kWh/m²y**	**kWh/m²y**	**%**	**kWh/m²y**	**%**
Year	20/07/2021	20/07/2022	365	1.01	8.78	7.08	80.6%	1.70	19.4%
Total	10/03/2019	19/01/2023	1441	0.96	8.54	7.08	82.9%	1.46	17.1%

Note: These consumptions are represented relative to the apartment's useful area of 82.42 m^2.

This value is significantly different from the average consumption in Spanish households. Generally, an average apartment in Spain allocates 57.9% of gas consumption for heating and 40.2% for DHW, with 1.9% used for cooking. In the northern region, this percentage is approximately 50% [83].

3.3.3. Electrical Consumption

The household's electric consumption is broken down annually in Table 19 due to the billing system of the electric supply company.

Table 19. Annual electric consumption.

Year	Start Date	End Date	Number of Days	kWh/Day	kWh/Year	kWh (Period)	kWh/m²y
2019	10/03/2019	31/12/2019	296	3.21	1172.72	951.03	14.07
2020	01/01/2020	31/12/2020	365	4.98	1816.06	1816.06	21.79
2021	01/01/2021	31/12/2021	364	5.95	2170.26	2164.31	26.04
2022	01/01/2022	31/12/2022	364	5.35	1953.87	1948.52	23.44
Total	10/03/2019	31/12/2022	1389	4.95	7112.91	6879.92	21.69

The average electricity expenditure per household in Spain is 3487 kWh per year, with apartments in buildings consuming 3373 kWh, according to the IDAE's Residential Sector Consumption Report [84]. For single-person homes, the consumption is around 2198 kWh/year, a figure close to the four-year average observed in the studied apartment.

The monthly breakdown of electric consumption is shown in the following Table 20, with a fairly regular consumption of around 1800–2200 kWh per year (22–27 kWh/m^2y).

Table 20. Monthly electric consumption distribution. Source: authors.

Sum of Monthly Consumption [kWh]					Monthly Consumption per Unit of Area [kWh/m²]				
Month	**2019**	**2020**	**2021**	**2022**	**Month**	**2019**	**2020**	**2021**	**2022**
Jan.	44.79	105.25	183.46	175.67	**Jan.**	0.54	1.28	2.23	2.13
Feb.	44.31	104.35	172.48	146.06	**Feb.**	0.54	1.27	2.10	1.77
Mar.	56.29	107.40	175.81	159.69	**Mar.**	0.68	1.30	2.14	1.94
Apr.	77.69	155.68	178.07	167.08	**Apr.**	0.94	1.89	2.16	2.03
May	101.00	151.56	189.75	168.52	**May**	1.23	1.84	2.31	2.05
Jun.	95.92	158.83	185.30	155.47	**Jun.**	1.17	1.93	2.25	1.89
Jul.	100.11	163.45	167.63	170.32	**Jul.**	1.22	1.99	2.04	2.07
Aug.	133.59	186.01	186.60	187.04	**Aug.**	1.62	2.26	2.27	2.27
Sep.	101.14	156.75	169.98	135.52	**Sep.**	1.23	1.90	2.06	1.65
Oct.	97.21	151.50	180.06	157.00	**Oct.**	1.18	1.84	2.19	1.91
Nov.	89.28	171.84	197.91	159.95	**Nov.**	1.08	2.09	2.40	1.94
Dec.	113.69	203.45	176.82	166.20	**Dec.**	1.38	2.47	2.15	2.02
Total	**1055.00**	**1816.06**	**2163.88**	**1948.52**	**Total**	**12.82**	**22.06**	**26.29**	**23.67**

Since March 2021, the mechanical ventilation system's operation has been monitored, with its electric consumption accounting for approximately 10% of the annual electricity usage in this apartment.

This comprehensive analysis of utility consumption provides insight into the building's performance in terms of water, energy, and electric usage, compared to regional and national averages. The data serves as a valuable reference for evaluating the building's efficiency and the effectiveness of its mechanical systems.

4. Discussion

Long-term monitoring has yielded several valuable insights which are detailed in this section, but first, the following limitations should be considered.

One of the inherent limitations of conducting real-world monitoring studies is the inability to control or measure all potential variables. In our case, the lack of data on window opening times, the dynamic nature of air leakage and ventilation, and precise occupancy schedules pose significant challenges. These unmeasured variables could influence the indoor environmental conditions and, consequently, our study's findings. Acknowledging these limitations is essential for understanding the study's context and the potential variability in thermal comfort and energy efficiency outcomes.

In addition, the selection of the specific apartment for this detailed analysis was primarily influenced by the unique opportunity presented by the apartment owner's willingness to participate in an extensive monitoring campaign. This participation allowed for the deployment of a wide array of monitoring equipment, ensuring a comprehensive data collection process over an extended period. The apartment's location within the Bolueta Tower, notable for being the tallest Passivhaus-certified residential building globally, adds a distinctive value to our study. While recognizing that the monitored apartment may not encapsulate the entire building's performance, its Passivhaus certification and the depth of data collected make it a significant case study.

Comfort models are indispensable tools for evaluating indoor environmental quality and occupants' thermal comfort. However, the models themselves are not without limitations. Their ability to accurately predict comfort levels can vary based on numerous factors, including but not limited to, the specific conditions of the monitored environment and the individual characteristics of the occupants, processes of adaptation and acclimatization. Recognizing these limitations is crucial for interpreting our study's results. Furthermore, there is a pressing need for ongoing research into developing and refining comfort models to enhance their predictive accuracy and applicability across diverse climates and building types. Recent studies, such as [85–87] highlight the evolving nature [88] of this research field and underscore the importance of continuous improvement in comfort modelling [89].

5. Conclusions

This article has quantified, for the apartment studied, the combined consumption of heating and DHW at 8.58 kWh/m^{2}y. Using an estimate of DHW consumption for the actual occupancy and based on the corresponding Spanish standard, the energy consumption for heating was estimated at 1.46 kWh/m^{2}y. This figure corresponds with habits previously collected in survey-based studies [13] and is significantly lower than that provided by other studies in colder climates, such as the 8.4 kWh/m^{2}y of Darmstadt-Kranichstein [59–61] or the 14.6 kWh/m^{2}y of Johnston et al. [62]—83 and 90% less energy, respectively.

Over 1389 days in the period 2019–2022, electricity consumption was quantified at 21.7 kWh/m^{2}y—39% lower than the average consumption per household based on [90]—although the occupancy of the apartment studied was lower than the average occupancy (one person vs. 2.38 persons per dwelling [57]), which might suggest higher than average electricity consumption per person. Additionally, the electricity consumption of mechanical ventilation with heat recovery was quantified at about 10% of the apartment consumption.

Regarding comfort, the apartment failed to meet the comfort requirements of the Passivhaus standard. During the periods analysed in 2020, 2021, and 2022, it received a catastrophic rating if we apply the PHI criteria. The interior temperature exceeded 25 °C for a very significant percentage of time in the months from May to October. Overheating was more severe in the studied bedroom than in the living room. For the entire period, both the bedroom and living room failed the CIBSE TM:59 criteria. The limit recommended by CIBSE Guide A for nighttime, 24 °C, was exceeded 23–43% of the time in the bedroom.

The variability of summer temperatures has a significant quantitative effect on the number of hours that exceed the comfort ranges of the dwelling. It is evident from the analysis that the summers of 2020 and 2022 were hotter than that of 2021. However, as shown in the Figures A4–A9 of Appendix B, which break down the temperature and relative humidity pairs over the three summers, the climate remains relatively mild, with many hours below the threshold of 25 °C.

It is apparent that other factors are adversely affecting the thermal comfort within the homes. As highlighted in the literature [5], overheating is not an inevitable outcome of nZEB or energy-efficient or "super-insulated" homes but rather a possible consequence of design decisions regarding glazed areas, orientation, provision of summer solar protection, wall insulation placement, ventilation, and a variety of other factors. In this case, we would add that apartment building typologies urgently require design modifications to facilitate the dissipation of internal heat, primarily through effective natural cross-ventilation in conjunction with increased use of materials with thermal mass.

Passive ventilation with cooler external air, particularly at night, is typically the main passive mechanism for heat removal. However, this leads to apartment building typologies with a low number of dwellings per communication core or shaft, as opposed to collective housing with 3, 4 or 5 dwellings per floor and served by one stair and elevator shaft. A significant issue in this building's typology is that ventilation is only found on one facade or on two non-opposing facades. The building's strong airtightness, coupled with the absence of windows on opposing facades, results in a considerable challenge in dissipating heat during the day. In addition, the interiors predominantly feature very light partitions, with virtually no inertia and are filled with mineral wool insulation, as customary in gypsum board construction.

The results of the analysis presented in Section 3 indicate that adaptive comfort models are not an effective analysis tool in this building. Despite the models suggesting that the dwelling remains within comfort zones for numerous hours, this does not coincide with the overwhelming majority of user's perception. It seems necessary to further investigate how these adaptive models perform against real world situations.

The studied building is located in a climate with relatively mild winters, an effect due to its proximity to the sea, which diminishes with distance from the coast. This means that the winter climate severity does not justify the excess insulation and airtightness proposed in the design of these homes. The potential health benefits of reduced exposure to cold are overshadowed by the effects that excessive heat has on the inhabitants. Particularly noteworthy are the high nighttime temperatures monitored, which the majority of surveyed residents identify as one of the major issues in their homes.

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Appendix A

This Appendix contains figures and data describing the exterior climate recorded in the Abusu meteorological station.

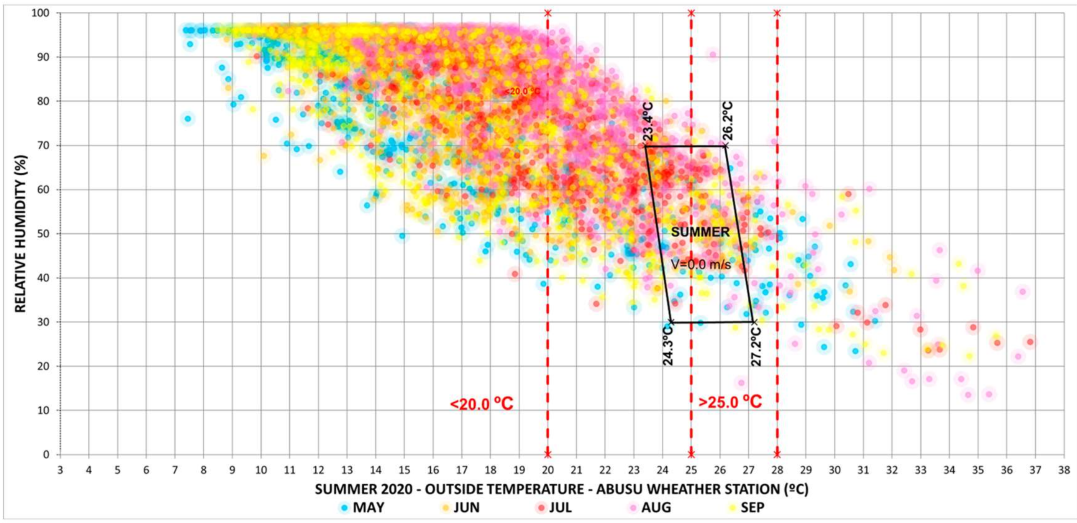


Figure A1. Temperature and RH pairs plot for summer 2020.

Table A1. Summary of statistical measures for exterior climate, summer 2020.

	Summer (3672 h)	May	Jun.	Jul.	Aug.	Sep.
Hours T < 20 °C	2434 (66.3%)	560 (72.6%)	591 (82.0%)	425 (57.2%)	374 (50.3%)	484 (67.2%)
Hours T > 25 °C	296 (8.1%)	60 (8.1%)	32 (4.4%)	51 (6.9%)	87 (11.7%)	66 (9.2%)
Hours T > 28 °C	88 (2.4%)	19 (2.6%)	7 (1.0%)	12 (1.6%)	29 (3.9%)	21 (2.9%)
Maximum T.	38.7 °C	31.4 °C	32.1 °C	38.7 °C	38.2 °C	35.6 °C
Hours R.H. > 70%	2293 (62.5%)	466 (62.7%)	493 (68.6%)	457 (61.5%)	513 (69.0%)	365 (50.8%)
Maximum R.H.	96.3%	96.3%	96.2%	96.2%	96.3%	96.2%

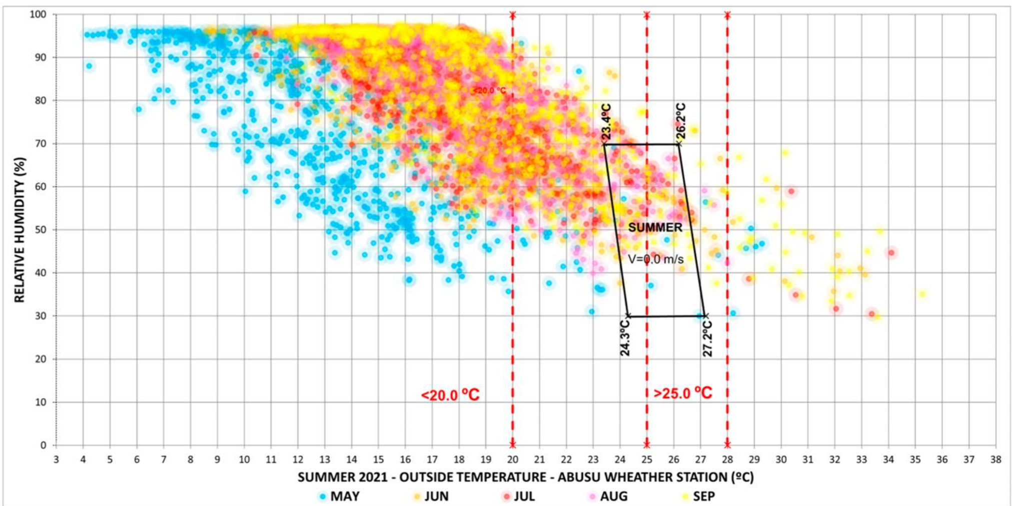


Figure A2. Temperature and RH pairs plot for summer 2021.

Table A2. Summary of statistical measures for exterior climate, summer 2021.

	Summer (3672 h)	May	Jun.	Jul.	Aug.	Sep.
Hours T < 20 °C	2788 (66.3%)	688 (92.5%)	565 (78.4%)	532 (71.5%)	513 (68.9%)	490 (68.1%)
Hours T > 25 °C	144 (3.9%)	11 (1.5%)	27 (3.8%)	26 (3.5%)	25 (3.4%)	55 (7.6%)
Hours T > 28 °C	48 (1.3%)	5 (0.7%)	9 (1.2%)	6 (0.8%)	0 (0.0%)	28 (3.9%)
Maximum T.	35.3 °C	29.3 °C	33.1 °C	34.1 °C	28.0 °C	35.3 °C
Hours R.H. > 70%	2543 (69.3%)	440 (59.2%)	514 (71.5%)	535 (72.0%)	526 (70.8%)	528 (73.4%)
Maximum R.H.	97.2%	96.2%	96.6%	96.3%	96.4%	97.2%

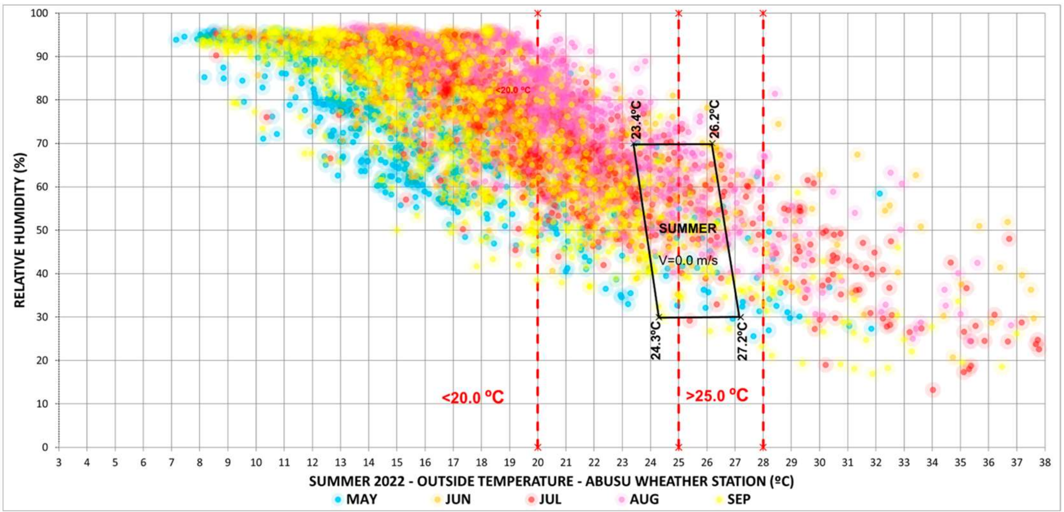


Figure A3. Temperature and RH pairs plot for summer 2022.

Table A3. Summary of statistical measures for exterior climate, summer 2022.

	Summer (3672 h)	May	Jun.	Jul.	Aug.	Sep.
Hours T < 20 °C	2303 (62.7%)	611 (82.1%)	517 (69.5%)	377 (50.7%)	309 (41.5%)	490 (68.1%)
Hours T > 25 °C	380 (10.3%)	39 (5.2%)	53 (7.4%)	115 (15.5%)	100 (13.4%)	73 (10.1%)
Hours T > 28 °C	190 (5.2%)	13 (1.7%)	30 (4.2%)	71 (9.5%)	40 (5.4%)	36 (5.0%)
Maximum T.	39.4 °C	32.1 °C	38.1 °C	39.4 °C	36.8 °C	37.0 °C
Hours R.H. > 70%	2283 (62.2%)	460 (61.9%)	515 (71.6%)	402 (54.1%)	494 (66.5%)	412 (57.3%)
Maximum R.H.	96.7%	96.2%	96.6%	96.3%	96.4%	97.2%

Appendix B

This Appendix contains additional graphs and plots describing the indoor comfort inside the studied apartment.

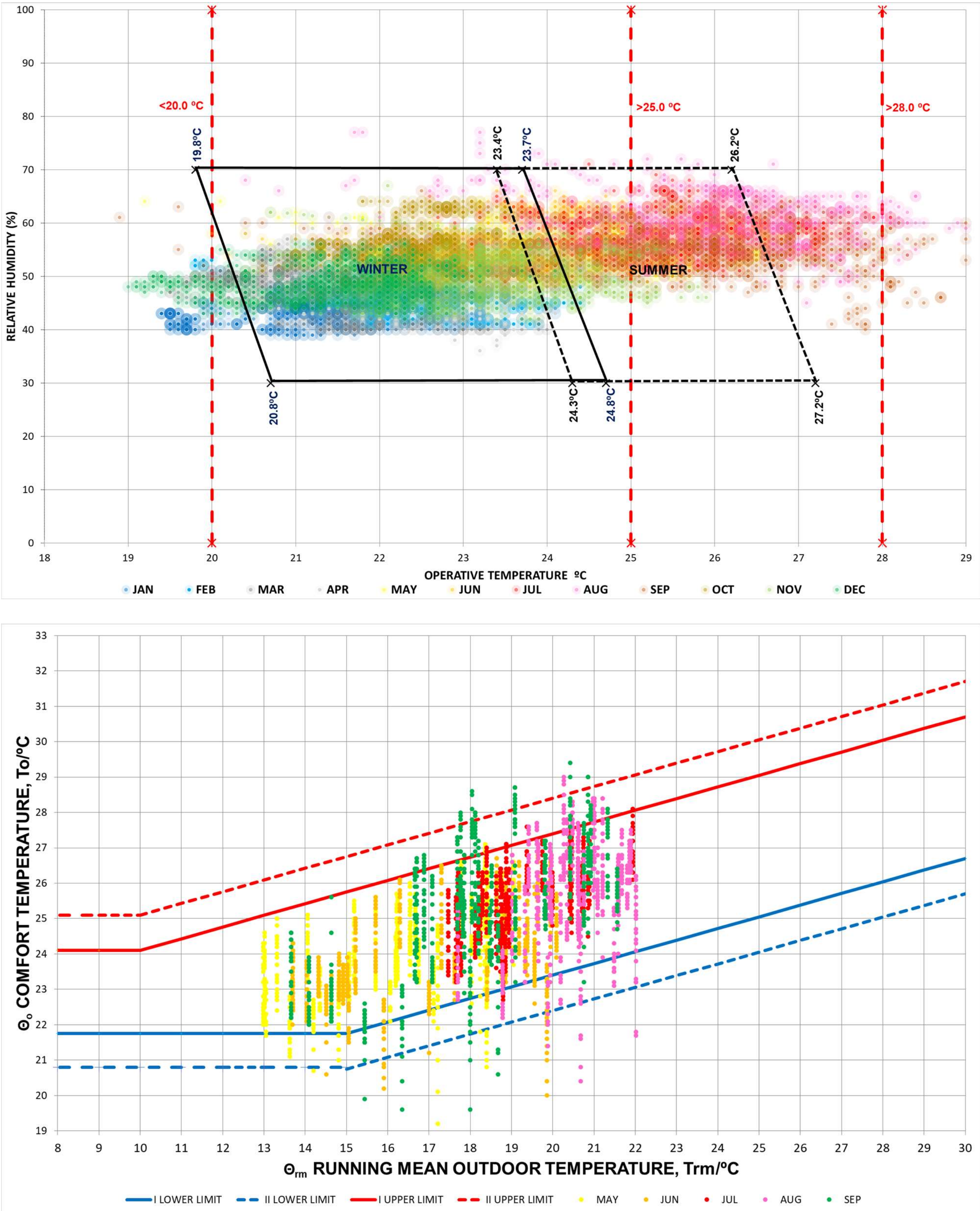
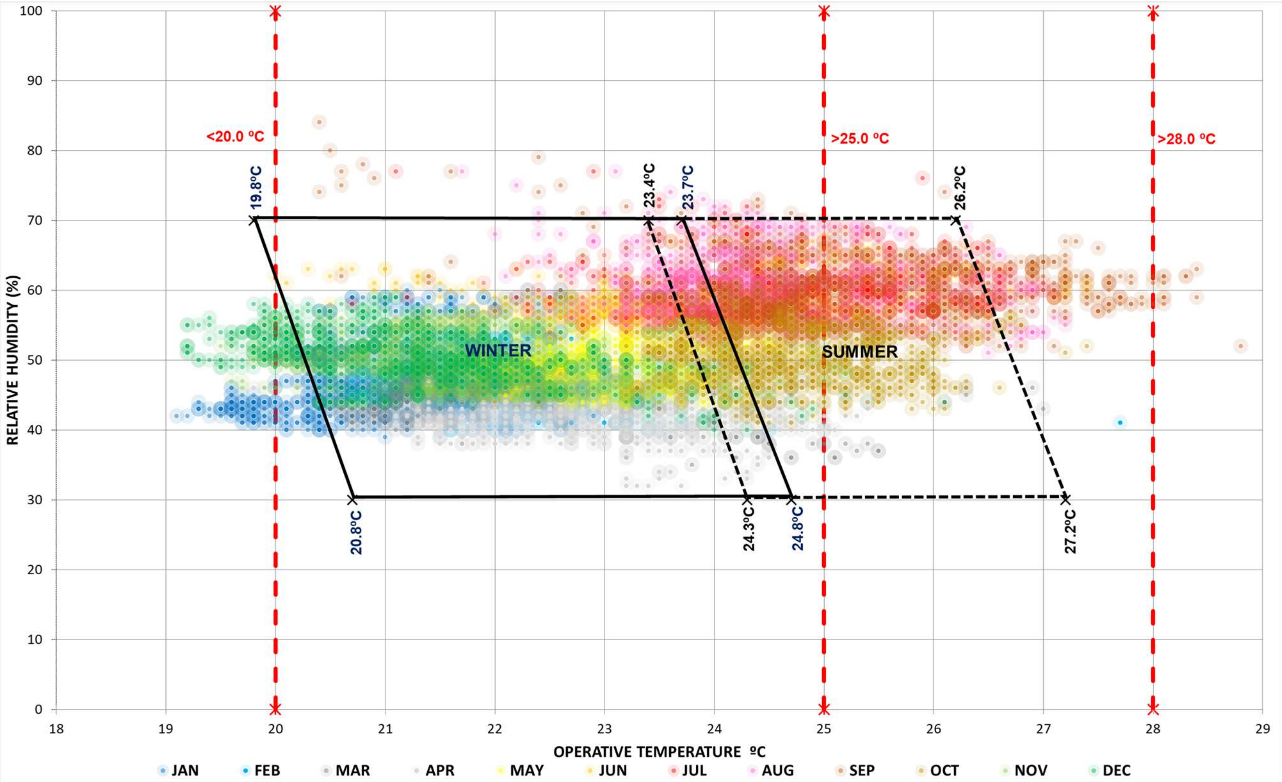


Figure A4. Living room comfort plots for year 2020.



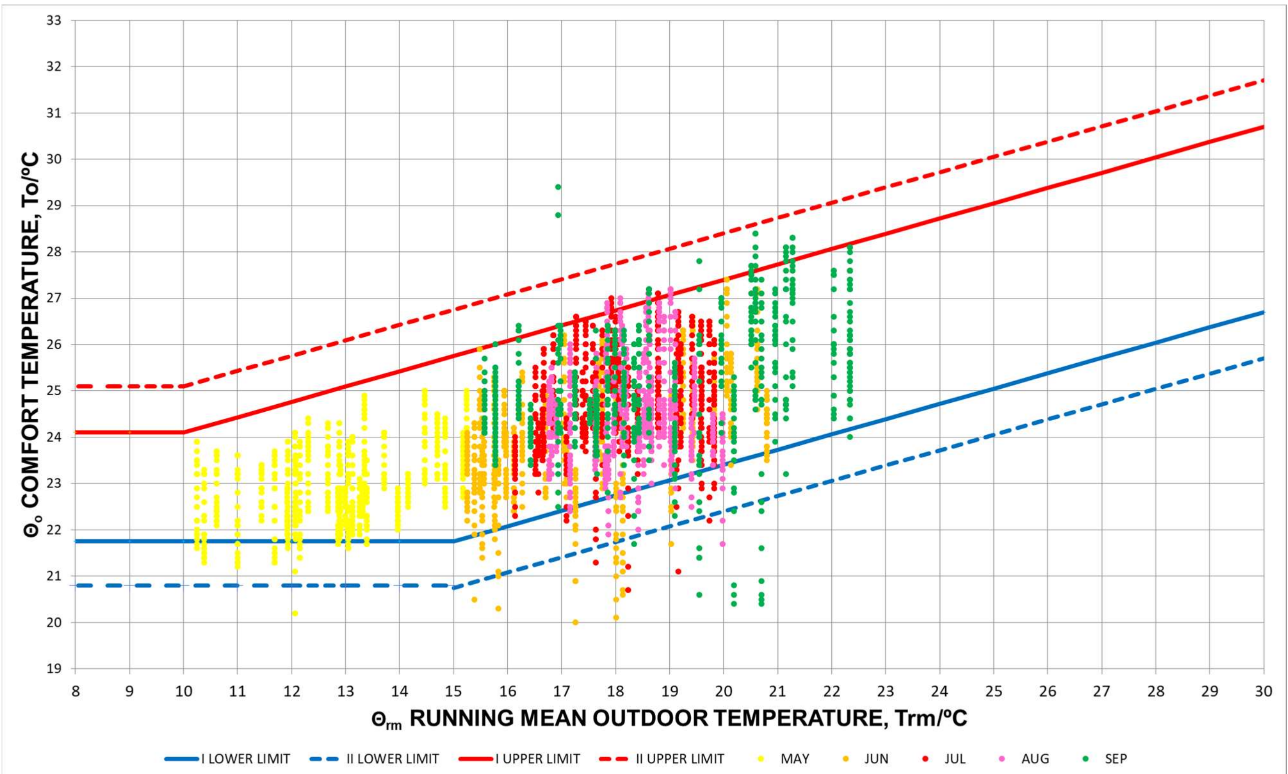
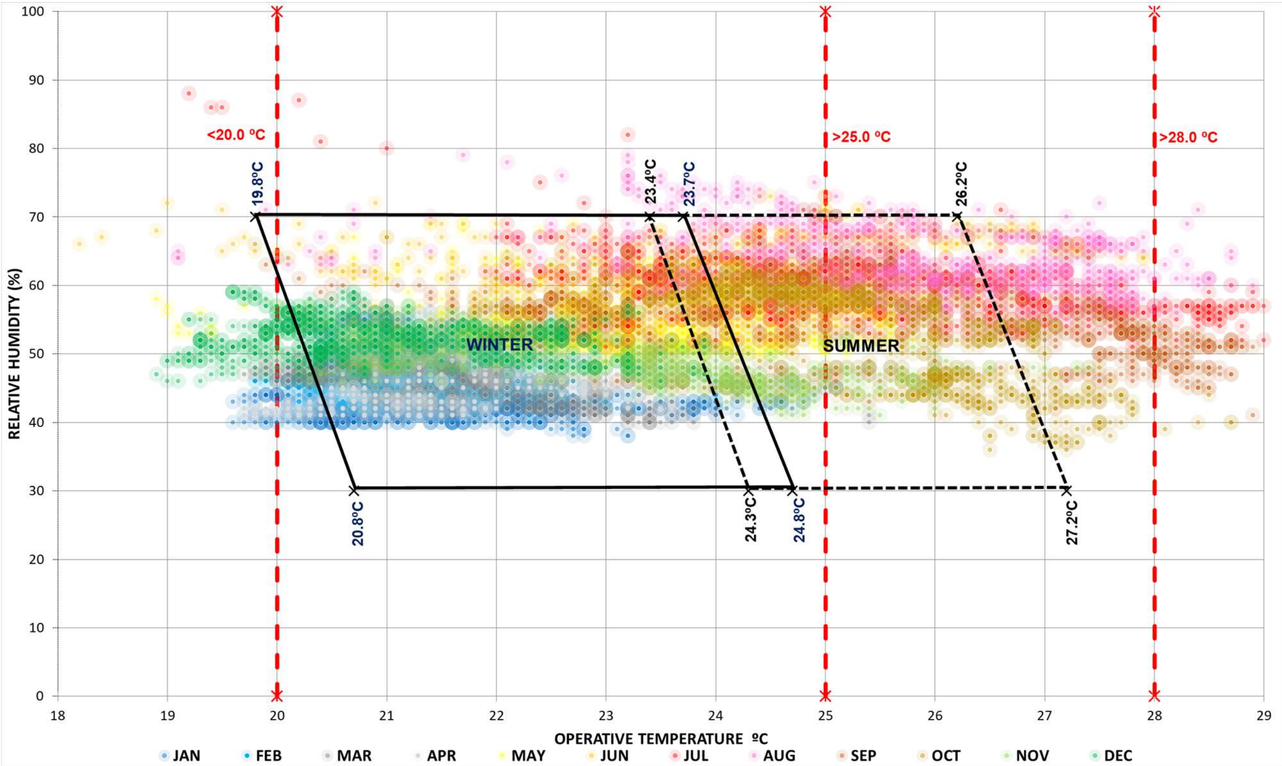


Figure A5. Living room comfort plots for year 2021.



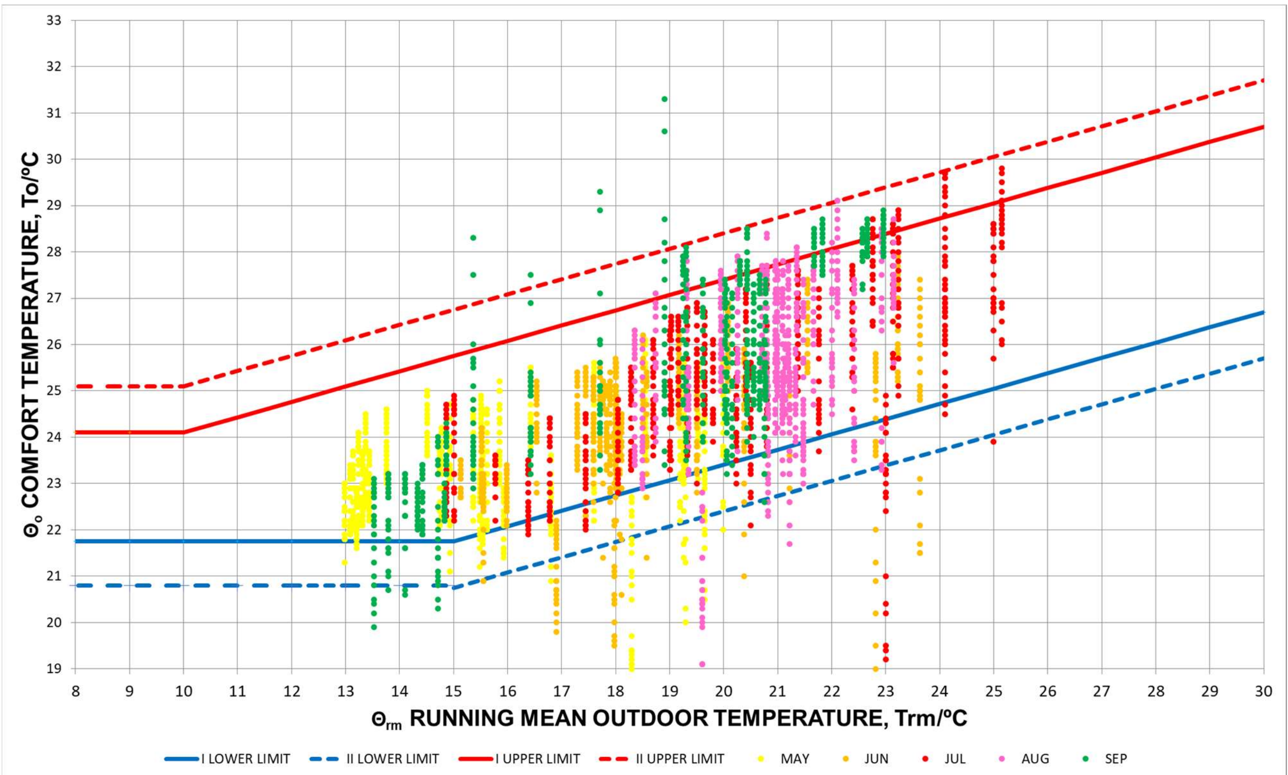


Figure A6. Living room comfort plots for year 2022.

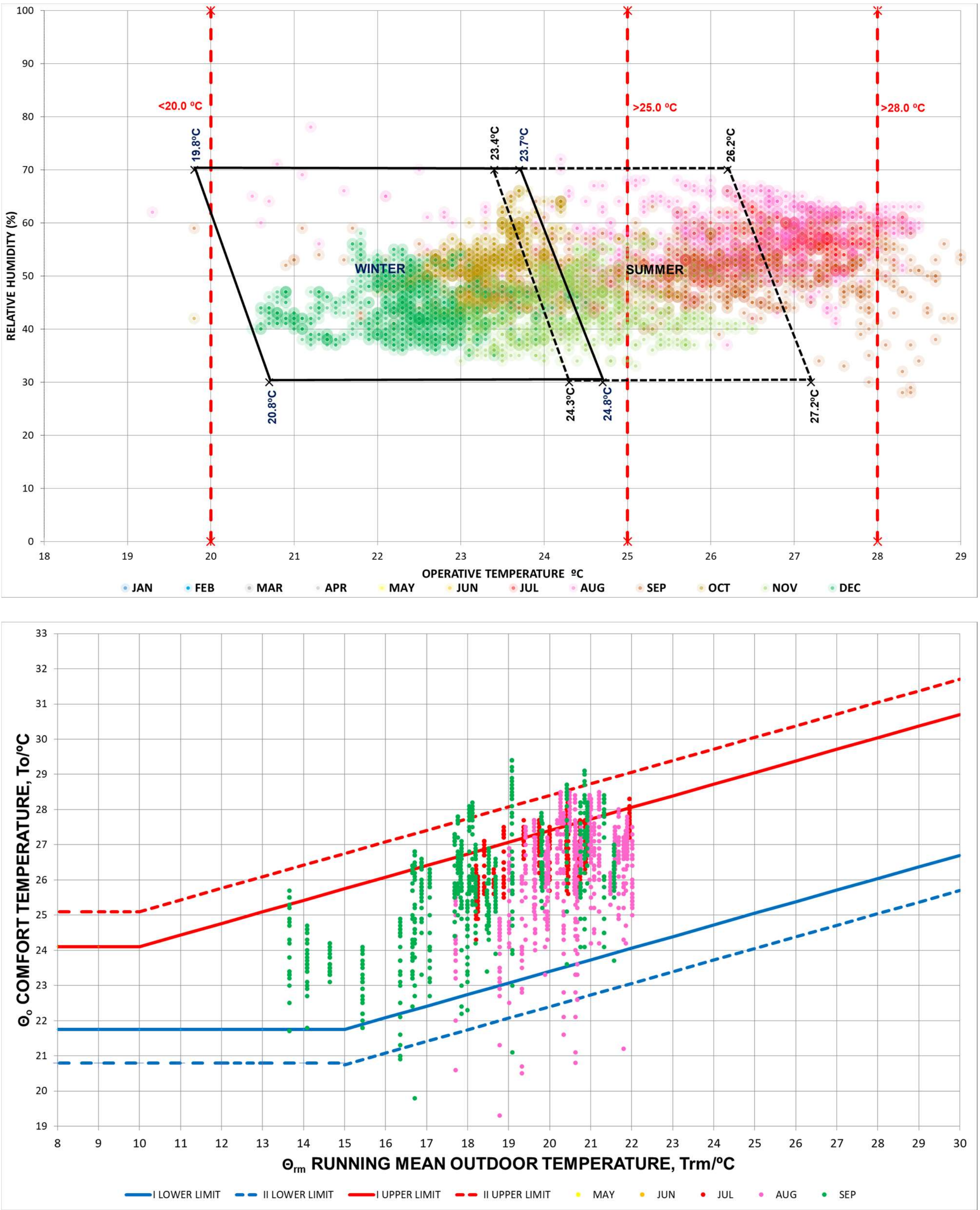


Figure A7. Bedroom comfort plots for year 2020.

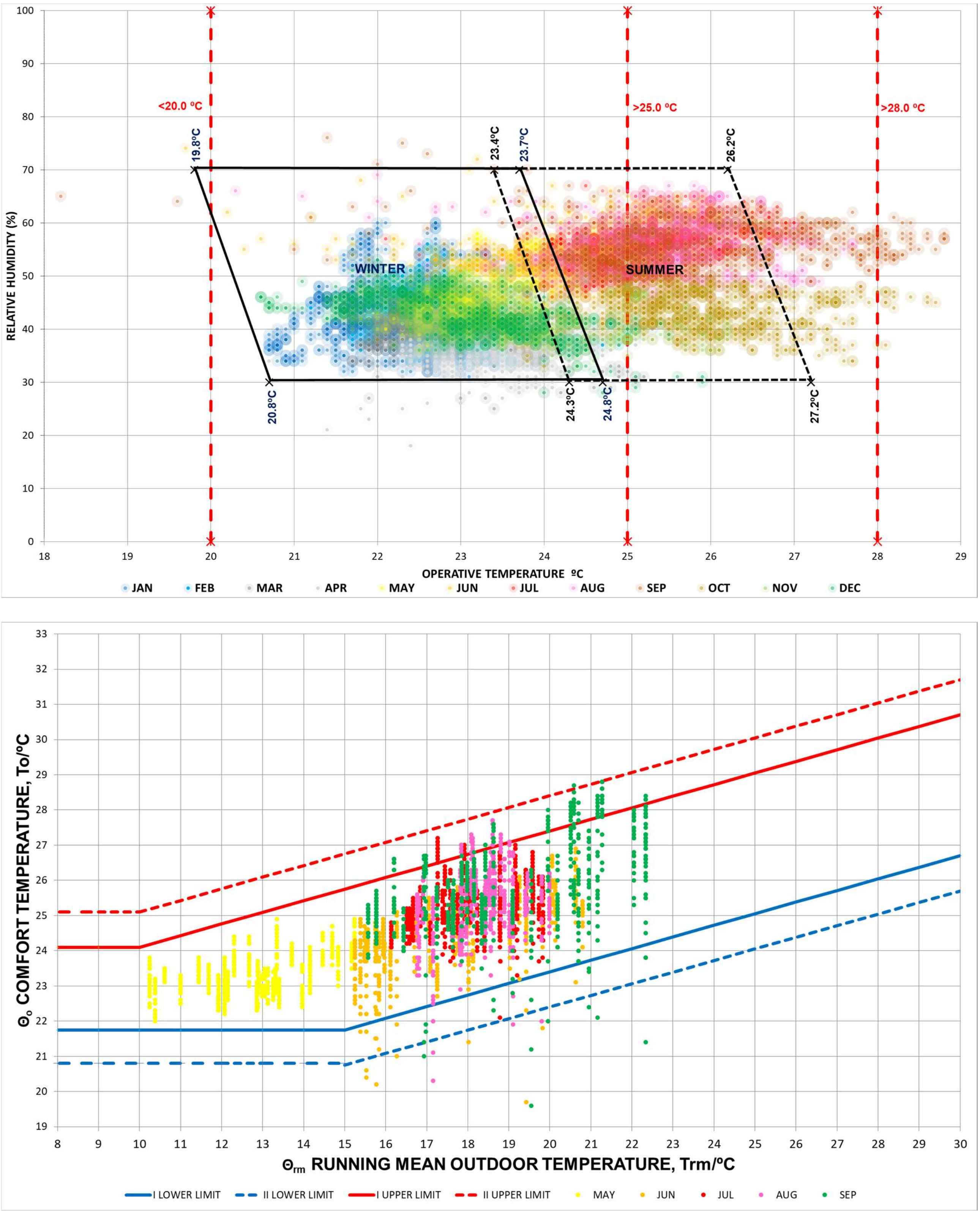


Figure A8. Living room comfort plots for year 2021.

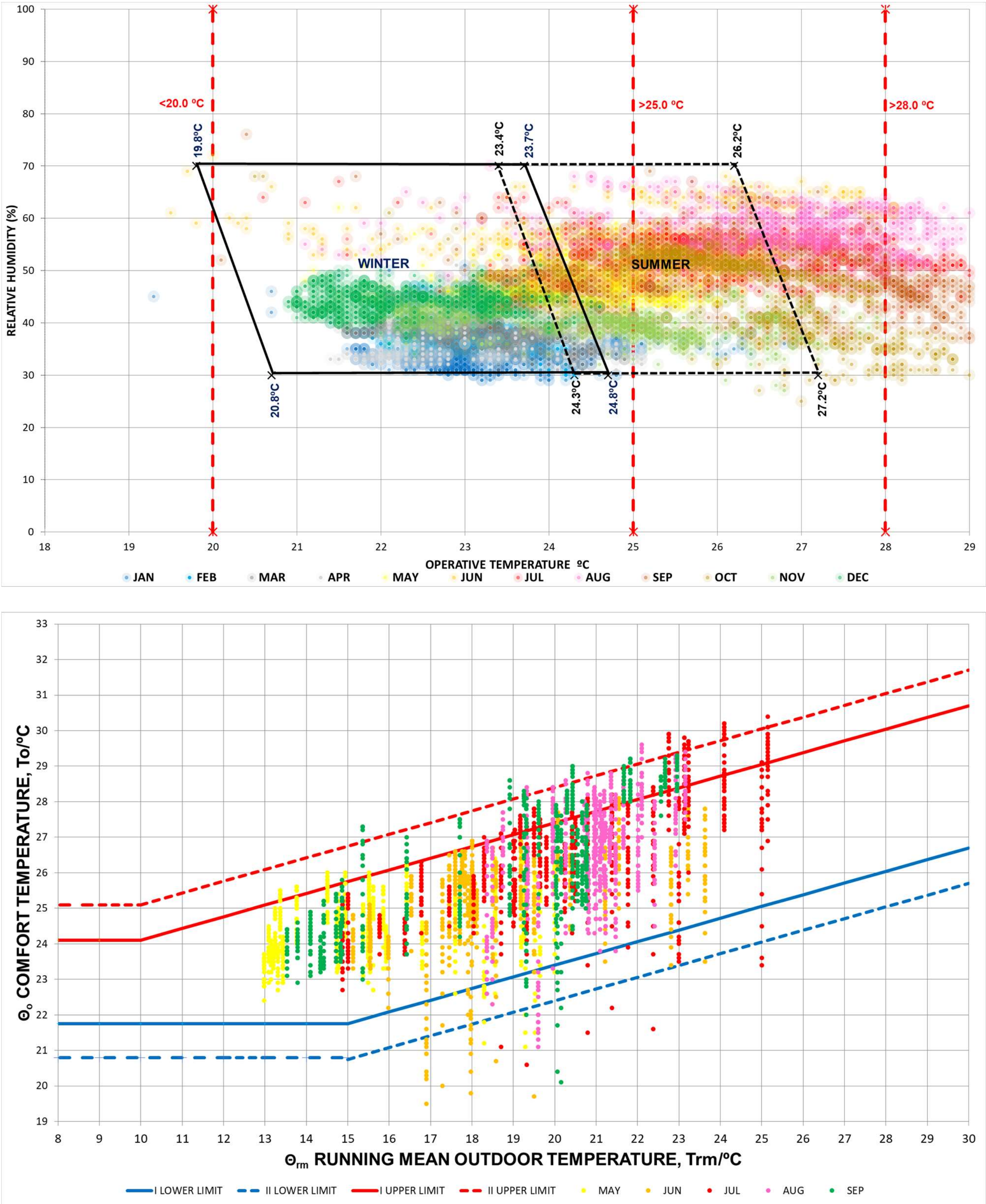


Figure A9. Living room comfort plots for year 2022.

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