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Indoor Environmental Quality and Consumption Patterns before and during the COVID-19 Lockdown in Twelve Social Dwellings in Madrid, Spain

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Abstract: This article analyses the situation that prevailed in 12 dwellings located on the outskirts of Madrid during Spain's state of emergency. How did 24/7 occupation affect the quality of indoor air and power consumption patterns? The mixed method used (surveys and instrumental monitoring) pragmatically detected the variation in consumption, comfort and indoor air quality patterns before and during the COVID-19 pandemic. The characteristics initially in place and household predisposition had a conclusive effect on such variations. The starting conditions, including household composition, habits and the way daily activities were performed, differed widely, logically affecting power consumption: 8/12 case studies increase occupancy density by more than 25 percent; 11/12 improve thermal comfort; 10/12 improve air quality but not necessarily translate in a sufficient ventilation practices; air quality was lower in the bedrooms on the whole; only 4/12 case studies use the potential of passive measures; only one household adopted energy savings strategies; 10/12 case studies increase electric power consumption but none of the dwellings was fitted with a renewable power generation system. The conclusion drawn is that, despite starting conditions differing widely, household composition, habits (including performance of daily activities performance) and power consumption also played an active role in the end result. This approach allowed to integrate qualitative and quantitative findings on indoor environmental quality (IEQ), energy use and households' behavior. The objective data on the energy situation of the case studies not only is useful for the study, but also for potential enrollment in energy rehabilitation programs, such as the European Regional Development Fund (ERDF).

Keywords: COVID-19; housing; lockdown; indoor air quality; CO_2 concentration; monitoring; consumption patterns; questionnaire; comfort; household behaviour

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1. Introduction

The SARS-CoV-2 pandemic has created a worldwide health emergency of historic impact [1]. Between the time cases of pneumonia of unknown origin were detected in Asia in December 2019 [2] and the confirmation of the first 10 cases in Europe, i.e., through 30 January 2020, 7818 cases had been diagnosed worldwide [3]. On 11 March 2020, the World Health Organisation (WHO) raised the SARS-CoV-2 epidemic to pandemic status [4]. Three days later, a state of emergency was decreed in Spain [5]. Three weeks later, the cumulative number of deaths in all European countries peaked at 88,581, nearly 35,000 in excess of the 50,000 normally expected [6]. Prior to that date, the WHO had issued a communiqué on the extreme public health measures to be adopted to prevent even worse consequences due to the propagation of the disease [7].

In Spain, as well as in other countries, lockdown was decreed as a protective, preventive or propagation containment strategy. In Spain, that entailed remaining indoors at home with very specific exceptions, as well as the closure of all educational institutions and furtherance of remote working wherever possible. As the state of emergency and preventive interruption of many activities had enormous economic and social impact, however, especially among the most vulnerable communities [8], the national Government sought and obtained Ministry of Health endorsement to ease restrictions for a gradual return to normality subject to the infection rates [9]. Lockdown gave rise to an unusual situation in which, beginning on 14 March and through 21 June, everyone was generally home-bound 24 h daily [10]. With households constantly occupying shared space, all activities, including those normally conducted in schools [11,12], offices [13] or out of doors [14] were concentrated in the home. For weeks, cities were relieved of mobility- and human activity-induced pressures [15–17], which were shifted indoors [18].

Years earlier, the WHO had alerted to the importance of housing on human health [19]. Dwelling conditions normally affect occupants' quality of life and life expectancy, as well as the onset or worsening of disease, whilst improved building design has consistently been associated with epidemiological event-based learning and the evolution to healthier habitation models [20]. Poor indoor air quality, the tenth avoidable health risk listed by WHO, and similar specific factors affect human health directly [21]. Some of those factors have been studied as well in connection with their possible impact on COVID-19 infection [22]. Housing has not in vain been included by the Spanish Government as a determinant in health-related social inequality [23].

Human beings normally spend over 90% of their lives indoors, where pollutant concentration is two- to five-fold higher than outdoors [24]. People may be more or less healthy depending on the quality of their indoor environment. Habitability may be defined essentially in terms of minimum occupation density and health- and safety-related standards such as hygiene along with infrastructure operation and maintenance to guarantee safe and pleasant surroundings. The objective in connection with thermal comfort is to maintain temperature and relative humidity within a range acknowledged as comfortable or sufficient for personal well-being [25,26]. Other items also addressed in indoor environmental quality studies include visual comfort and natural lighting [27,28], air quality (in turn related to the ventilation needed to eliminate or dilute suspended or deleterious pollutants and provide a source of clean air) [29,30] and acoustic comfort [31].

In addition, lockdown has directly or indirectly induced significant change in behaviours and home usage [32]. Any number of studies on the psychological impact of lockdown have been conducted to understand how compulsory confinement within the home has been experienced, along with the situations arising, associated primarily with stress, anxiety and other adverse effects on the population's emotional health. Housing layout and other home attributes have been observed to play a part in such issues [33].

The questions identified as being in need of in-depth analysis included: what is happening at home? What changes in habits and everyday life have been brought on by lockdown? How have those changes affected dwellings? Did dwellings adapt well to household needs? What shortcomings were detected? What indirect impact did lockdown have on health, over and above COVID-19 infection? Finally, what desirable home improvements were identified by households? All the foregoing issues have been addressed from the standpoints of power consumption, indoor environmental quality and personal well-being in domestic surroundings. Very few studies have focused on indoor environmental quality, housing comfort or power consumption patterns and their possible impact on life, for the priority in lockdown as an emergency public health measure was to protect the population against infection and provide a safe environment via social distancing.

The HABITA-RES project was underway during lockdown [34]. The project consisted in assessing power use by recording consumption and indoor air quality data in inefficient housing on the outlying districts of Madrid to detect opportunities for building rehabilitation. The availability of that database afforded an occasion to analyse the situation prevailing before and during lockdown to identify the implications of the intense housing usage resulting from such exceptional circumstances.

The interest and relevance of this study in the current literature on COVID-19, housing and households and their interaction in extreme conditions of confinement is developed in the following section in more detail. In particular, aspects based on indoor environmental quality (including thermal comfort) as well as energy consumption in the home are exposed.

2. Literature Analysis

The literature in the field of energy use in the home, and especially during the COVID-19 confinement period, has been approached in different ways, depending on the object of study and the aspect or scale to be addressed. At more general levels, a significant decrease in energy demand has been observed, although confinements due to social isolation have increased consumption associated with housing [35–37]. This alteration would entail important changes in the household economy [38], especially for the most vulnerable population segments [39].

Some of these studies have unevenly addressed how it has affected these sectors of the population socioeconomically and in relation to health, according to the access to minimum comfort and energy, for the performance of daily life in this unusual context [40–42], including the risks associated with physical and psychological well-being [43,44]. Others have listed solutions adopted by governments and public institutions to support these vulnerable households in these times of uncertainty and need [45–47]. Furthermore, some of these studies vindicate the role of housing inefficiency in aggravating the energy vulnerability, even poverty, of these households [48]. However, this aspect seems to be not specifically included in recovery strategies and measures related to COVID-19 in general terms [49].

More specifically, the literature on the housing indoor environment and households' well-being in the confinement context, is approached from different scopes and territorial scales.

Some of the studies analyzed the domestic energy globally [16]. Others focused either on specific collectives, or comparing certain domestic facilities and supplies before and during pandemic, for instance, cooking [50] or the availability of cooling/heating devices [51].

In Spain, this panorama has not been different from that experienced globally in other developed countries [52,53], also considering the alleviation measures available for vulnerable people [54]. Other research approached other scales, such as regional or urban ones, even separating by consumers, but with no consideration of lifestyles, habit changes and the housing performance from a dual perspective of household-dwelling and bearing in mind the incidence of the confinement itself [55].

Analogously, derived from the relocation of work [56,57] and telestudy by school closure [12], many daily commutes were avoided [58]. In addition, for those people working in essential jobs, safer and individual displacement modalities were boosted, such as walking [59], cycling [60] and even running [61]. This mobility change led to better environmental indices due to a decreasing pollution of outdoor air, a reduction of fossil-fuel intakes, and therefore, of generated emissions [62–64]. The outdoor air pollution could aggravate cases of people affected by coronavirus [65]. In turn, the permanence of people in the home together and for a long time, could lead to an overexposure to certain environmental pollutants or potentially harmful agents, such as volatile organic compounds (VOC), radon, formaldehyde, CO and CO_2 and moisture, among others [30,66]. This overexposure could lead in turn not only to the generation or worsening of health problems, but to affect the well-being of people already subjected to certain stress and other discomforts due to the very unusual circumstance itself [67,68].

In this sense, more people staying inside their homes for a longer time clearly affects the production of CO_2, which can only be alleviated to the extent that good ventilation habits are practiced in proportion to such permanence [69]. Furthermore, these habits have been especially promoted due to the aerosol transmission of SARS-CoV-2 [70], being that CO_2 is a great tracer to indirectly measure the level of space ventilation, and thus, to evaluate the potential exposition to inhale the coronavirus.

In the same way, the humidity generated by human activity depending on the type of activity, by latent heat, as well as by the use of certain equipment, must also be counteracted with evacuation systems, by dilution with outside air [71]. Finally, the role of indoor temperature is vital to guarantee a comfortable environment that allows the well-being of people, thus avoiding problems that affect daily life, as well as the performance of activities and the health of its inhabitants. At the same time, if energy consumption, which is presumed increased by the greater permanence in the home of all the cohabitants [72], can also give an idea of the satisfaction of comfort in the home.

Especially during the COVID-19 pandemic, the energy and indoor environmental aspects in housing need to be considered in ways that realistically reflect households' experiences, including their daily life, possible alterations in behavior and routines, affecting energy consumption, occupancy, and ventilation and lighting habits, among others [73].

Therefore, a shortage of studies is perceived that comprehensively disclose the households' behaviors and their relationship with the changes in habits and routines in terms of energy consumptions for each facility or supply, thermal comfort and indoor environmental quality in general in order to solve new and former needs in the domestic milieu. This analysis contributes to a better understanding, from a mixed perspective of detailed and quality home data, on how public health measures such as confinement affect the population and, therefore, their lives, with impacts in their social, economic, safety and health scopes, derived from the consequences on energy consumption and the quality of the indoor environment.

The aim of this study consisted of analysing the factors in which COVID-19-induced lockdown affected everyday life in vulnerable homes in the city of Madrid, and specifically in terms of comfort, indoor environmental quality and energy use. In addition, the specific objectives were: (1) define to what extent there was an alteration in the daily life and performance of the case-study homes, determining the causes and concrete consequences in the interior environmental quality and energy consumption; (2) quantify and qualify the alterations produced in previous domestic settings, comparatively in the periods before/during confinement; and (3) assess the comparison between the perception of such factors reported by surveyed respondents and the objective values of the respective parameters delivered by sensors installed in the living room and master bedroom.

Occupant behaviour has significant impact on power consumption and indoor environmental quality [74,75]. Therefore, two research questions were posed: Q1: Did power consumption, environmental behaviour or indoor comfort vary in vulnerable homes under the exceptional circumstances imposed by COVID-19? If so, how?; and Q2: Were significant differences identified between what home dwellers perceived and objective instrumental data?

A mixed method is applied based on questionnaires and monitoring. In addition to the surveys that help to detail the realities of each home before and during the pandemic, three parameters of the indoor environment usually chosen to be monitored in the dwellings are also used in this analysis: temperature, humidity and CO_2, along with energy consumption. This also allows the related analysis of people's behavior in the domestic environment, including those guidelines that directly affect indoor environmental quality, energy consumption and indoor comfort in homes in a comparative way that considers both normal circumstances and confinement.

This mixed method, as will be developed in Section 3, offers a more complete and enriched understanding of the reality lived in confinement. In addition, unlike many other studies, this one offers information on twelve social dwellings in a European capital, such as Madrid (Spain), covering all the main deprived areas of the city, geographically well distributed throughout the urban area, which gives a special interest to the study. This study also took advantage of the opportunity through a broader project, HABITA_RES. This could facilitate a longitudinal analysis, comparing not only the monitoring of the two periods, before and during the COVID-19 confinement, but also the declared data by respective surveys. In fact, the contact already maintained with the households also allowed for the access to any behavioral or routine change, as well as the collection of newly declared data. In this way, a common discourse merging from the two perspectives and techniques under the mixed method approach differs from what is commonly exposed in other studies where a mere separate analysis is given from each approach, either quantitative, or qualitative one.

The further purpose of the researchers is to contribute to the current literature addressing the real needs of the most vulnerable users that should be borne in mind in design and rehabilitation geared toward decarbonisation and energy transition [33]. More specifically, it analysed such needs under the extreme circumstances spawned by confinement to living quarters decreed to contain the COVID-19 pandemic.

3. Materials and Methods

The HABITA_RES project [34] monitored a sample of 22 dwellings in six multi-family buildings, each in a different neighbourhood on the outskirts of Madrid (Figure 1).

Figure 1. Case studies in six neighbourhoods on the outskirts of Madrid.

Of the 22 dwellings covered in the project, 12 were analysed as case studies, labelled as follows: CS1, CS2 in San Blas (brown), CS3, CS4 in Manoteras (cyan), CS5, CS6 in Carabanchel (red), CS7, CS8, CS9 in Orcasitas (magenta), CS10, CS11 in Fuencarral (blue) and CS12 in Villaverde (green). All households, with the exception of the flat in Orcasitas which was included in the sample for its deficient construction and refurbishment planned for the near future, were built as social housing prior to 1980 when the insulation requirements stipulated in code NBE CT-79 entered into effect.

Table 1 summarises the general characteristics of each dwelling: year of construction, general upkeep, usable area, building type, orientation-exposure to the sun, type of most immediate surrounds and power source and facilities. The information was drawn from the two surveys described in Section 3.2; the public information on record with the cadastre (year of construction and dwelling floor area [76]) or the Ministry for Development's Secretariat of State for Infrastructure, Transport and Housing (thermal characteristics as defined in keeping with the year of construction [77]). All the aforementioned general characteristics are described in detail, for they affect energy behaviour and, consequently, consumption associated with maintaining thermal comfort and indoor air quality.

Table 1. General characteristics of dwellings studied.

		Dwelling Characteristic												
Category	**Factor**	**CS1**	**CS2**	**CS3**	**CS4**	**CS5**	**CS6**	**CS7**	**CS8**	**CS9**	**CS10**	**CS11**	**CS12**	**Legend**
Dwelling Characteristic	Neighbourhood	San Blas	San Blas	Manoteras	Manoteras	Carabanchel	Carabanchel	Orcasitas	Orcasitas	Orcasitas	Fuencarral	Fuencarral	Villaverde	Location in Madrid
	Storey	01/03	02/03	05/05	05/05	01/06	06/06	04/10	09/10	10/10	04/05	04/05	01/02	Storey/total storeys
	Year const.	1960	1960	1965	1968	1965	1965	1982	1982	1982	1965	1965	1950	Source: cadastre
	General upkeep	G	G	G	D	G	G	D	D	D	D	D	D	P: poor; D: deficient; G: good
	Condition of windows	G	G	G	G	D	G	G	D	G	G	G	P	P: poor; D: deficient; G: good
	Area (m^2)	110	115	70	72	73	117	110	110	110	91	93	74	Source: cadastre
	Tenancy	O	O	O	O	O	O	O	O	O	O	O	T	O: owner; T: tenant
	Building type	1	1	1	1	2	2	2	2	2	1	1	1	1. Residential building. 2. Residential building compatible with other uses
	Building typology	SA	SA	SA	SA	BC	BC	SA	SA	SA	SA	SA		SA: stand-alone BC: block
	Orientation-sun exposure	E + W	Sunny	Sunny	Sunny	E	Sunny	N + S	Sunny	N + S	N + S	N + S	Sunny	Sunny: entire dwelling receives sunlight at different times of day E: east; W: west; S: south; N: north Shady: presence of obstacles
	Skirted by	WS	WS	NS	L	NS	L	L	L	WS	L	L	WA	L: landscaping WA: wide avenue WS: wide street NS: narrow street
DHW	System	Individual	Individual	Individual	Individual	Individual	Individual	Individua	Individual	Individual	Individual	Individual	Individual	
	Power source	NG	NG	E	NG	Gasoil + E	E	NG	NG	NG	NG	NG	E	E: electricity; NG: natural gas
HEATING	System	Individual	Individual	Individual	Individual	Communal	Communal	Individual	Individual	Individual	Individual	Individual	Individual	Individual/Communal
	Power source	NG	NG		NG	Gasoil	Gasoil	NG	NG	NG	NG	NG		NG: Gas Natural; Gasoil.
	Facility/system	HP		HP + EF					HP				EF	HP: heat pump; EF: electrical facility

This study deployed a mixed method [78–81] as a pragmatic approach to data collection on variations in consumption, comfort and indoor air quality before and during the COVID-19 pandemic, and the detection of any significant differences between user perception and the sensor-logged values for the parameters were analysed. The mixed method consisted in integrating the qualitative, survey-collected data using questionnaires with alternating open- and close-ended questions [82–85] and the quantitative information obtained instrumentally to explain and validate the findings. Data interconnection was based on explanatory sequential design and data merging [80]. The former used the qualitative data to explain and interpret the key quantitative findings. Data merging deploys a common language to perform simultaneous triangulation in which data compiled from different sources are used [85] to confirm, corroborate or cross-validate findings. The mixed method approach followed is illustrated in Figure 2.

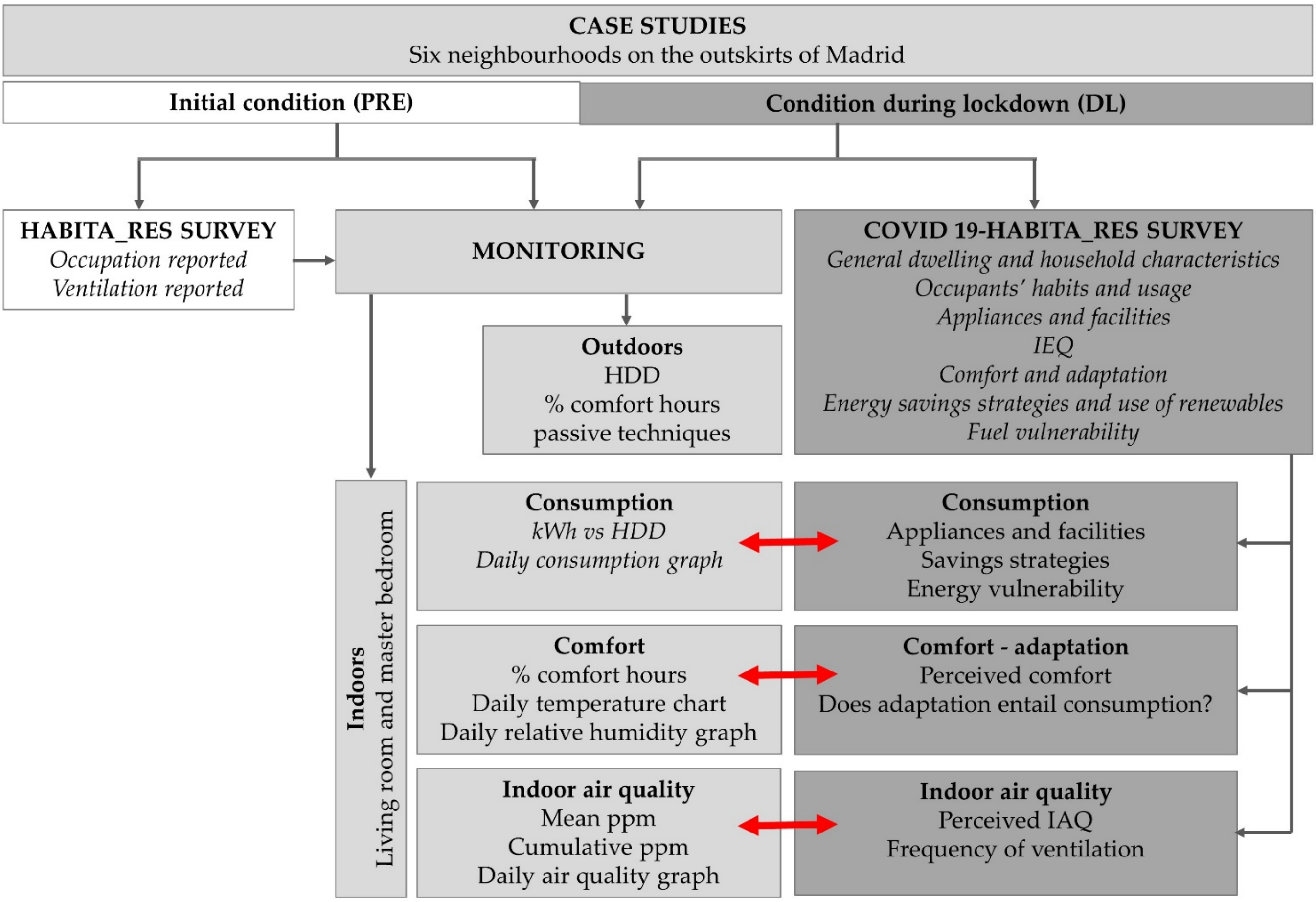

Figure 2. Mixed method flow chart.

3.1. Study Timeframe

A state of emergency was officially called in Spain on 14 March 2020 in an attempt to contain the COVID-19 infection [5]. This study analysed the indoor environmental quality and power consumption data recorded between 7 March 2020 00:00 and 20 March 2020, i.e., 7 days before and 7 days during the state of emergency. The aim was to ascertain the effects of 24/7 dwelling use on comfort, indoor air quality and power consumption patterns under similar weather conditions.

3.2. Surveys

The study drew information from two surveys. The first, conducted from March 2018 to September 2019, primarily to design the monitoring model to be used in the dwellings [86], included questions on building and dwelling characteristics, energy and ventilation habits, HVAC systems and power consumption history. The second was conducted from 4 to 14 May 2020 to collect information on the perception of reality in dwellings during the COVID-19 lockdown. It contained questions on changes in habits and type of activities performed in the period; the relationship to spaces in the home, the use of electrically powered heating/DHW utilities and facilities and household energy behaviour in connection with indoor activities, flat use and occupation during the sole state of emergency called to date in Spain. Inasmuch as the timeframe for this analysis ran from 7 to 21 March 2020, the primary source of qualitative data was the second, COVID-HABITA_RES survey, although the earlier HABITA_RES survey findings were also used to validate and supplement those data.

Table 2 lists the variables on the COVID-HABITA_RES questionnaire. It is an original resource that came from the Spanish project [COVID-HAB], on confinement by COVID-19, housing and habitability [18]. Their researchers were involved in both inquiries. This questionnaire was partially adapted to aim the objectives of this study. The information collected in that survey was grouped under six categories to describe power consumption, environment and comfort in homes during lockdown.

Table 2. COVID-HABITA_RES survey categories and variables.

Category	Variables
Household characteristics	Family members: minors (<18); seniors (>65); occupation density; rise in occupation density
Habits	Household tasks; remote working; outings; altered habits
Power-consuming facilities	Household appliances and comparative use; digital hardware and comparative use; domestic hot water; source of power and comparative use; heating, type of system and use during lockdown
Indoor environmental quality	Natural lighting; air quality; acoustic comfort; frequency of window opening and comparative practice; frequency of use of shading devices; existence of spaces open to outdoors
Comfort and adaptation	Apparel-based adaptation; type of adaptation to dissatisfaction with heating; perceived thermal comfort; preferred range of temperatures
Energy savings strategies and use of renewables	Savings strategies, use of renewable energy

The first item addressed the main compositional characteristics of the household, including the number of residents under 18 and over 65 and the occupation density defined as the ratio between the number of dwelling users and usable area. The occupation density (no. people/m^2) and its variations were estimated for all the dwellings studied to determine where intensity of use was altered.

User habits were defined on the grounds of their responses to a question on the relative time devoted to a series of tasks scored on a five-point Likert scale [87], where 1 was least and 5 was the most time. In addition, in connection with habits, they were asked whether they were able to work from a home office and the number of persons engaging in remote working in the home; the establishment of routines similar to pre-lockdown practice or otherwise; outings and most frequent justification; and alteration or otherwise of habits during lockdown.

The category on dwelling facilities entailing power consumption covered the main household appliances and a comparison of their use before and during lockdown, including: computer hardware; domestic hot water systems and comparative frequency of use; and heating systems, type of power used and frequency of use during lockdown.

The three indoor environmental quality variables were natural lighting, indoor air quality and acoustic insulation. Although that was the information collected with the survey, as the comparative study focused on indoor air quality, the frequency of window opening and use of shading devices was also compared. An item was likewise included on whether or not the dwelling had spaces open to outdoors.

Under the category on comfort and adaptation respondents were asked about their perception of thermal comfort, apparel-based adaptation, preferred type of heating in the absence of thermal comfort and household thermal preferences as defined in standards ASHRAE 55 [25] and ISO 7730 [26].

The energy saving strategies and renewable use category was built around variables on the strategies deployed by households to save energy during lockdown and the availability in the dwelling of renewable energy-powered systems.

The category on energy vulnerability, in turn, alluded to all variables describing household risk of fuel poverty or of the aggravation of that situation. The category variables were perceived vulnerability, the need for emergency financial aid to relieve the situation, the percentage of income normally devoted to power expenses compared to expenses during lockdown and, where no power bills referring to the lockdown period had yet been received when the survey was completed, any expected change in expenditure.

3.3. Monitoring

The sensors installed in each dwelling [86] recorded data on electricity (kWh), where appropriate and possible, natural gas (m^3) consumption at 10 min intervals and on temperature (°C), relative humidity (%) and CO_2 (ppm) concentration in the living room and master bedroom. All the buildings involved were fitted with a weather station to record local weather conditions.

Simple data gathering models were designed with internet of things (IoT) technology to lower costs and minimise inconvenience for the dwellings monitored, although user availability proved to be essential. Table 3 lists the technical specifications of the sensors used. The data on the dwellings were stored on the monitoring platform [88] designed for the HABITA_RES project and the weather station data on the opensource data platform Weather Underground (Available online: www.wunderground.com, accessed on 20 March 2020). As the stations on the buildings in Carabanchel and Orcasitas recorded barely any data in the period studied, information was downloaded from a nearby station.

The data recorded were processed and managed in the Jupyter Notebook for the Anaconda Python language [89]. The Python modules used were: Pandas v1.2.4 (Available online: http://pandas.pydata.org, accessed on 12 April 2021) for data analysis; Geopandas v0.6.3 (Available online http://geopandas.org, accessed on 24 September 2019) for geometric and spatial data analysis; and Bokeh v2.3.2 (Available online: https://bokeh.org, accessed on 12 April 2021) for visualisation.

Table 3. Sensors. Technical specifications.

Sensor Model-Type		Parameter	Range	Accuracy
Froggit WH3000	Temperature—humidity	Temperature	−40–60 °C	+/− 1 °C
	Temperature—humidity	Relative humidity	10–99%	+/− 5%
	Precipitation	Precipitation	0–6000 mm	+/− 10%
	Wind speed	Wind speed	0–50 m/s (0~100 mph)	+/− 1 m/s (wind speed < 5 m/s) +/10% (wind speed > 5 m/s)
	UV/LUX	Light	0–200 kLux	+/− 15%
Airsense	Temperature—humidity	Temperature	5–50 °C	+/− 0.4 °C
	Temperature—humidity	Relative humidity	0–80%	+/− 4%
	Carbon dioxide CO_2)	CO_2		+/− 50 ppm, +/− 3% of reading
Powersense	Electricity consumption and generation	Consumption	<80 A, 20 W–20 kW	-
Plugsense	Outlet consumption	Consumption	<13 A	-
Relaysense	Gas consumption	Consumption	>10 ms pulse interval	-

The data records for each dwelling are summarised in the worksheets reproduced in the Appendix A and described briefly below.

- Meteorological data: Givoni chart and daily temperature and relative humidity graphs (hourly medians). The reference lines on the latter represent the values recommended in Spanish legislation (CTE DB HS, 2019) and the base temperature (normally 65 °F = 18.33 °C) used to calculate heating degree days, a parameter that is explained below.
- Indoor environmental quality (IEQ) in the living room and master bedroom: Givoni chart and daily temperature, relative humidity and air quality curves (hourly medians). The reference lines on the graphs represent the values recommended in Spanish legislation (CTE DB HS, 2019).
- Electricity and natural gas consumption data: consumption-heating degree day graph relating outdoor conditions to consumption and daily consumption patterns (hourly medians).

The Givoni chart [90] is a psychrometric graph, i.e., it takes air temperature and relative humidity into account to assess the sensation of thermal comfort. The contour lines forming closed spaces on the chart denote the dimensions of the improvements needed to ensure comfort. Givoni charts were used to determine whether indoor and outdoor temperature (°C) and humidity (%) lay within the comfort zone. On these charts, temperature was plotted in terms of water vapour pressure (Pa) as per the Equation:

$$PV = \frac{HR \times \left(611 \times e^{0.0725 \times T - 0.0002881 \times T^2 + 0.00000079 \times T^3}\right)}{100}$$

where:

- PV is water vapour pressure in Pa
- HR is relative humidity (%)
- T is temperature (°C).

The information is synthesised as percentage of hours in the comfort zone prior to (PRE) or during (DL) lockdown. The comparison was supplemented with daily (based on hourly median) temperature and relative humidity graphs. The Givoni charts plotted with the data recorded by the weather stations were used to determine the presence or otherwise of differences in the weather in the two periods. The relative humidity graphs for the living room and bedroom before and during lockdown were analysed to determine whether or not conditions prevailing in the dwellings, hour-by-hour met comfort requirements, as well as any differences between the two periods.

Indoor air quality. Indoor CO_2 concentration is widely used to assess perceived indoor air quality and as an indicator of actual ventilation rates [91–94]. Standards ISO 17772, EN 16798, EN 15251, ASHRAE 62.1 and ISHRAE 10-0-01 recommend different CO_2 ceilings relative to the environmental level [95]. Here, the criterion used to assess air quality in the dwellings monitored was as set out in the Spanish legislation on residential buildings [96]. CO_2 concentration-based air quality was classified in terms of as Good (<900 ppm), Acceptable (900 ppm to 1600 ppm) or Poor (>1600 ppm). Mean and cumulative values of over 1600 ppm were the grounds for defining interperiod differences. The comparison was supplemented with daily (hourly median) indoor air quality graphs for the two periods.

Potential of passive measures: this indicator was analysed to show the percentage of hours with optimal indoor environmental quality (IEQ) and outdoor comfort. Where comfort was reached outdoors at a specific time of day and indoor comfort levels with good IEQ were reached at that same time, the dwelling was assumed to be capitalising on the potential of favourable outdoor conditions.

Heating degree days (HDD) and power consumption. Heating degree days was the parameter used to synthesise weather data. HDD is found by finding the difference between a base temperature (normally 65 °F = 18.33 °C) and the mean hourly air temperature throughout the heating period (here, the definition distinguished between before and during lockdown), disregarding the hours when the outdoor temperature is higher than the base value. Assuming a standard building requires no heating when the outdoor air is higher than the base temperature, this parameter provides an approximate measure of the amount of heat energy required (in this case, also affording insight into changing consumption patterns) [97]. Heating degree days calculated as shown below were plotted against the total consumption in the two periods and the indoor and outdoor temperatures in the two periods were likewise graphed to complete the comparison:

$$HDD = \sum_{i=0}^{168} \frac{MAX\left(T_{base\ heating} - T_i,\ 0\right)}{24}$$

where:

- $T_{base\ heating}$ is base heating temperature
- T_i is hourly mean temperature
- I is hours, to a total of 168

3.4. Joint Analysis of Reported and Monitored Data

Further to the answers given by users in the 12 dwellings to the 63 questions posed in the first questionnaire and the subsequent variable clustering as specified in Section 3.2, these parameters were reviewed to determine how they might be compared to the instrumental data or how they impacted the assessment of the power situation prevailing in the dwelling prior to or during lockdown. Variables were consequently defined on dwelling and household information (starting data) as well as on indoor environmental quality, comfort and consumption, which were deemed appropriate for comparison to the data recorded by the sensors. The other variables drawn from the questionnaire were used as controls to verify the absence of inconsistencies or as explanatory variables to support hypotheses on the situations actually in place. Depending on the information obtained for each variable, distinctions could be drawn between PRE and DL data.

The parameters were reorganised for comparison from two perspectives: (a) before and during lockdown; and (b) survey and instrumental data. The survey answers were subsequently simplified and univocally recoded to be able to assess how each parameter was affected (higher, lower, unchanged) relative to the initial conditions. Such simplification and subsequent recoding resulted in the generation of a common language to compare the survey results (with categorical responses in different formats such as Likert scales) to the sensor-logged data on indoor and outdoor environment and power consumption parameters. A comparison of the survey data to the quantitative data logged by the sensors provided an initial indication of possible alterations in the comfort, indoor environmental quality and power consumption patterns during lockdown.

The two types of data (subjective from the survey and objective from monitoring) were compared via recoding using a common six-point Likert scale (very poor, poor, mediocre, acceptable, good, very good) for the initial (pre-lockdown) conditions. A seven-point Likert scale (very much lower, much lower, lower, the same, greater, much greater, very much greater) was then defined to globally assess the variation in the parameters during lockdown relative to the pre-pandemic situation. That exercise involved a certain degree of synthesis to establish a common language for the two data sources, as well as constant advances and backtracking in analysis, recoding and decision-making to ensure that no significant information was left out in the process. Defining a common language also entailed validating the information collected, for in this mixed estimate, the control and explanatory variables served to confirm the data and justify the respective values.

The monitored and survey data are depicted in Figure 3, which shows the clusters as well as the control and explanatory parameters drawn from the survey and the data used to determine the pre-lockdown conditions for dwellings and households. Those initial parameters were used to restructure the information for the comparison and determine how lockdown was experienced in each household and the degree of variation or alteration in the three variables considered (comfort, indoor environmental quality, power consumption) in each dwelling.

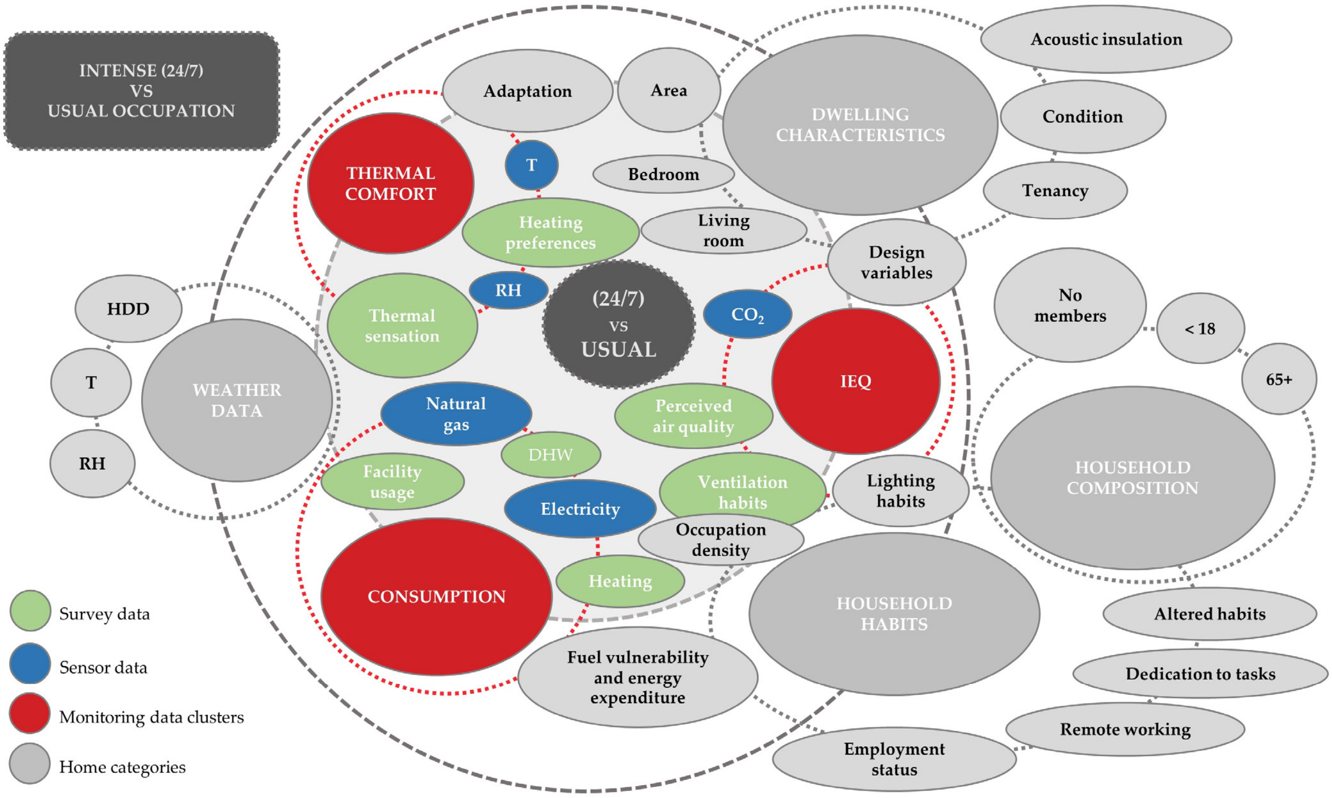

Figure 3. Survey and monitoring data clusters.

4. Results

The survey data parameters, clustered by category, are given in Tables 4 and 5. Table 4 lists the values reported by each household for indoor environmental quality, power consumption and heating facilities under the categories defined. Table 5 summarises the information on dwelling use and occupation, perception of comfort, energy expenditure relative to total income, fuel vulnerability as appropriate and user habits during this period.

Tables 6 and 7 summarise the indicators for the data logged by the sensors. Table 6 gives the values for the weather station parameters: degree days; the mean, maximum and minimum temperature (°C); the percentage of comfort hours (%); the electricity and gas consumption (kWh); variations in such consumption (kWh); and the relationship between outdoor conditions and consumption (slope on linear regression curve). Table 7 gives the pre-lockdown and during-lockdown living room and master bedroom IEQ parameters: the mean, maximum and minimum temperature (°C); the mean relative humidity (%); the percentage of indoor comfort hours and percentage of indoor–outdoor comfort hours; and the mean and cumulative air quality (CO_2 in ppm).

Table 8 contains a unified summary on a common scale of the survey- and sensor-collected information for each dwelling, comparing lockdown to the pre-pandemic values. The respective data are shown for dwellings grouped under the headings PRE, DL and neighbourhood.

Table 4. Indoor environmental quality, power-consuming facilities and use of heat during lockdown (survey data).

Indoor Environmental Quality, Power Facilities and Heat Use in Dwellings														
Category	**Factor**	**CS1**	**CS2**	**CS3**	**CS4**	**CS5**	**CS6**	**CS7**	**CS8**	**CS9**	**CS10**	**CS11**	**CS12**	**Legend**
Indoor Environ-Mental Quality	Natural lighting	2	2	3	2	2	4	3	3	3	4	2	2	1: None/scantly adequate; 2: Adequate; 3: Highly adequate; 4: Wholly adequate
	Air quality	3	3	4	3	2	4	4	3	3	4	1	1	1: Poor; 2: Mediocre; 3: Good; 4: Very good
	Acoustic insulation	2	2	4	2	1	3	1	1	2	3	2	1	1: No/insuff. ins. 2: Sufficiently ins. 3: Well ins. 4: Wholly insulated
	Windows	3 (4)	3 (4)	3 (3)	4 (4)	3 (4)	3 (3)	3 (3)	4 (4)	4 (4)	4 (4)	3 (3)	4 (4)	1: Closed/Unused Open/in use; 2: A few times/week 3: Once daily 4: Several times/day 5: Open/in use
	Shading devices	3 (5)	4 (4)	5 (5)	5 (5)	4 (4)	3 (3)	4 (4)	4 (4)	4 (4)	3 (3)	4 (3)	4 (4)	
	Spaces open to outdoors	No	Yes OUB	No	No	Yes RC	Yes ORB	Yes CB	Yes CB	No	Yes ORB	No	No	ORB.: Open roofed balcony OUB.: Open unroofed balcony CB: Closed balcony RC: Rear courtyard
Kitchen Appliances	Hob	EGC (=)	EGC (=)	EGC (+)	EGC (=)	EGC (=)	EI (=)	NG (=)	EGC (+)	E. V (=)	EI (+)	EGC (=)	EI (=)	EGC: Electric, glass ceramic EI.: Electric, induction NG: Natural gas (+): greater use; (=): same use; (−): less use during lockdown
	Oven	+	=	+	=	+	=	=	+	=	+	+	=	
	Clothes washer	=	=	=	=	+	−	=	+	−	−	−	=	
	Dishwasher	=	=	+	=	+	=	=	+	=	+		=	
	Other appliances (> use during lockdown)					F D			F D KR RV	RV	KR RV			F: Freezer; D: Dryer; KR: Kitchen robot; RV: Robot vacuum

Table 4. *Cont.*

Indoor Environmental Quality, Power Facilities and Heat Use in Dwellings														
Category	**Factor**	**CS1**	**CS2**	**CS3**	**CS4**	**CS5**	**CS6**	**CS7**	**CS8**	**CS9**	**CS10**	**CS11**	**CS12**	**Legend**
Digital And Internet Facilities	Internet	ADSL or similar	ADSL or similar	ADSL +mobile	ADSL or similar	ADSL or similar	ADSL or similar	ADSL or similar	ADSL or similar	ADSL + mobile	ADSL or similar	ADSL or similar	ADSL or similar	
	Mobile devices	+	+	+	+	+	=	+	+	+	+	+	+	
	Computer	+	+	+	+	=	+	+	+	+	+	+	=	
DHW	Use during lockdown	+	=	−	=	+	=	=	+	=	−	=	=	(+): greater use; (=): same use; (−): less use during confinement
Heating	Use during lockdown	As necessary	As necessary	Never	As necessary	Continually	Quite a lot	Quite a lot	As necessary	As necessary	Almost never	Never	Almost never	
Savings	Strategy	2	-	2	0	0	3	0	6	0		6	0	(10 strategies were suggested)

Table 5. Dwelling use and occupation, comfort, income and power expenditure, vulnerability and habits during lockdown (survey data).

Use and Occupation, Comfort, Energy Expense/Income and Vulnerability Parameters														
Category	**Variable**	**CS1**	**CS2**	**CS3**	**CS4**	**CS5**	**CS6**	**CS7**	**CS8**	**CS9**	**CS10**	**CS11**	**CS12**	**LEGEND**
Household Characteristics	No. members	5 (5)	2 (2)	1 (1)	2 (2)	3 (3)	3 (3)	3 (3)	4 (4)	5 (5)	4 (4)	2 (2)	4 (3)	
	No. <18	3				1	1			3	2	1		
	No. >65		1						1					
	Occupation density	4.55	1.74	1.43	2.78	4.12	2.56	2.78	3.64	4.55	4.44	2.15	5.41	
	Incr. occ. dens.	29.17%	14.58%	54.16%	37.50%	29.17%	30.56%	34.72%	35.42%	25.00%	33.33%	14.58%	11.11%	
Comfort and Acclimation	Thermal comfort level	2	3	3	1	3	3	3	2	2	3	4	1	1: Cool; 2: Slightly cool; 3: Neutral; 4: Slightly warm
	Apparel	1	2	2	3	2	2	2	2	2	2	1	2	1: Scant; 2: Normal; 3: Warm
	Adaptation	Windows	Apparel	Apparel	Heating	Windows	Apparel	Apparel	Windows	Apparel	Windows	Apparel	Apparel	

Table 5. *Cont.*

Use and Occupation, Comfort, Energy Expense/Income and Vulnerability Parameters														
Category	**Variable**	**CS1**	**CS2**	**CS3**	**CS4**	**CS5**	**CS6**	**CS7**	**CS8**	**CS9**	**CS10**	**CS11**	**CS12**	**LEGEND**
Income- Power Expenditure	Usual power expend.	10–15%	5–10%	NS/NC	10–15%	10–15%	5–10%	10–15%	10–15%	5–10%	NS/NC	5–10%	10–15%	
	Power expend. in lockdown	>15%				>15%	5–10%	10–15%	>15%	10–15%		5–10%	10–15%	
	Unbilled power expend.		Scant	Quite a lot	Scant						Quite a lot			
Fuel Vulnerability	Vulnerability during pandemic	No	No	No	No	No	No	No	Yes	No	No	Yes	No	
	Aid					Applied for						Received		
Habits	Remote working?	-	1	0	1	1	+1	+1	+1	+1	-	0	-	
	Primary activity	C	TV	H L S	RW H C	TV R C	RW	RW	L RW H C	C H	RW H C	TV H C	TV H	C: Care; TV: Television; H: Housework; L: Leisure; S: Sport; RW: Remote working; R: Rest
	Employment status	Chronically ill										Self	Retired	
	Frequency of outings	N	CN	O	TD	CT	O	CT	O	CT	CN	TD	CN	N: Never; AN: Almost never; O: Occasionally; AD: Almost daily; D: daily.

Table 5. *Cont.*

Use and Occupation, Comfort, Energy Expense/Income and Vulnerability Parameters														
Category	**Variable**	**CS1**	**CS2**	**CS3**	**CS4**	**CS5**	**CS6**	**CS7**	**CS8**	**CS9**	**CS10**	**CS11**	**CS12**	**LEGEND**
	Habits most intensely altered	W S SR	W S S/B	L SR	M L EL SR	W CC SM S/B SR	L DR S FS SR	W SR	W CC CL OH S FS SR	W CR E S L SP SR	W CC CL OH E L SP FS SB SR	L SP SR	CR S L SP FS SR	W: Work; S: Sleep; SR: Social relations; S/B: Shower/bath; L: Leisure; CC: Childcare; FS: Free space; SM: Smoking; CL: Cleaning; OH: Other housework; SP: Sport; DR: Dressing; E: Eating

Table 6. Weather and power consumption (sensor-logged data).

Sensor-Logged Data													
Category	**Variable**	**CS1**	**CS2**	**CS3**	**CS4**	**CS5**	**CS6**	**CS7**	**CS8**	**CS9**	**CS10**	**CS11**	**CS12**
Outdoor	Weather station	ICONIL1	ICONIL1	IMADRI16	IMADRI16	IMADRID279	IMADRID279	IMADRID279	IMADRID279	IMADRID279	IMFUENCA11	IMFUENCA11	IMVILLAV10
	HDD before	36	36	37	37	30	30	30	30	30	36	36	34
	HDD during	46	46	48	48	41	41	41	41	41	47	47	42
	Mean T before	13.66	13.66	12.19	12.19	14.13	14.13	14.13	14.13	14.13	13.64	13.64	14.15
	Mean T during	11.71	11.71	11.37	11.37	11.99	11.99	11.99	11.99	11.99	11.64	11.64	12.54
	Max T before	24.33	24.33	24.39	24.39	25.56	25.56	25.56	25.56	25.56	24.42	24.42	25.17
	Max T during	22.14	22.14	22.64	22.64	21.06	21.06	21.06	21.06	21.06	22.58	22.58	22.64

Table 6. *Cont.*

		Sensor-Logged Data											
Category	**Variable**	**CS1**	**CS2**	**CS3**	**CS4**	**CS5**	**CS6**	**CS7**	**CS8**	**CS9**	**CS10**	**CS11**	**CS12**
	Min T before	3.22	3.22	1.50	1.50	2.94	2.94	2.94	2.94	2.94	3.08	3.08	3.33
	Min T during	4.14	4.14	3.72	3.72	4.83	4.83	4.83	4.83	4.83	4.28	4.28	4.61
	% comf. h before	14%	14%	8%	8%	17%	17%	17%	17%	17%	15%	15%	16%
	% comf. h during	3%	3%	3%	3%	1%	1%	1%	1%	1%	3%	3%	5%
Power Consumption	Power cons. (kWh) before	99.29	34.89	45.84	56.72	60.39	N/D	51.02	40.77	53.76	67.68	33.70	131.28
	Power cons. (kWh) during	116.98	33.54	65.69	57.33	69.87	N/D	49.01	48.13	73.17	85.79	35.08	132.79
	Incr. pwr cons.	17.82%	−3.87%	43.30%	1.08%	15.70%	N/D	−3.94%	18.05%	36.10%	26.76%	4.09%	1.15%
	Linear reg.: elec. pwr cons. vs. HDD before	0.86	0.60	0.37	−0.03	0.86	N/D	0.55	0.33	0.19	−0.05	0.17	2.33
	Linear rge. pwr. cons. vs. HDD during	0.10	−0.05	−0.14	0.11	0.16	N/D	0.46	0.37	0.51	−0.09	−0.04	0.04
	Natural gas cns. (kWh) before	152.57	243.71	-	N/D	-	-	N/D	53.12	N/D	N/D	N/D	-
	Natural gas cns. (kWh) during	123.08	250.85	-	N/D	-	-	N/D	27.61	N/D	N/D	N/D	-
	Incr. natural gas cns. (kWh)	−19.33%	2.93%	-	N/D	-	-	N/D	−48.02%	N/D	N/D	N/D	-
	Linear reg.: natural gas/HDD before	3.51	3.89	-	N/D	-	-	N/D	2.41	N/D	N/D	N/D	-
	Linear reg.: natural gas/HDD during	0.52	0.92	-	N/D	-	-	N/D	0.01	N/D	N/D	N/D	-

Table 7. IEQ in living room and bedroom (sensor-logged data).

		Data Logged											
Category	**Variable**	**CS1**	**CS2**	**CS3**	**CS4**	**CS5**	**CS6**	**CS7**	**CS8**	**CS9**	**CS10**	**CS11**	**CS12**
Living Room	Mean T before	21.03	21.84	19.30	18.57	24.03	N/D	21.19	21.68	21.36	22.29	21.68	22.42
	Mean T during	21.58	22.41	20.42	19.92	23.68	N/D	21.70	21.60	21.98	22.27	22.50	23.05
	Max T before	22.70	23.40	22.50	21.95	26.60	N/D	23.50	23.85	24.80	24.85	23.60	27.90
	Max T during	23.40	23.80	23.30	22.63	26.17	N/D	23.40	23.90	25.00	24.30	23.62	28.00
	Min T before	19.10	20.62	16.73	16.30	21.60	N/D	19.50	19.70	18.70	20.60	19.77	19.85
	Min T during	19.77	20.80	18.65	17.75	21.55	N/D	20.00	19.90	19.40	20.48	21.22	20.52
	Mean RH before	68.32	54.28	81.34	56.33	57.17	N/D	40.02	41.00	71.20	46.06	48.95	57.39
	Mean RH during	71.09	54.27	79.25	53.23	60.67	N/D	42.21	42.07	70.31	47.83	46.20	59.17
	% comf. h before	85%	100%	4%	27%	100%	N/D	89%	95%	69%	100%	95%	99%
	% c¡omf. h during	92%	100%	8%	39%	100%	N/D	100%	98%	90%	100%	100%	99%
	% outd. comf. h+IEQ before	0%	29%	0%	15%	7%	N/D	96%	100%	21%	58%	85%	0%
	% outd. comf. h+IEQ during	0%	0%	0%	40%	0%	N/D	100%	100%	100%	100%	100%	0%
	Mean IAQ before	1966	1368	1913	918	1408	N/D	822	893	1154	1029	1064	2263
	Mean IAQ during	1939	1284	2152	806	1602	N/D	771	736	1035	1050	1029	1722
	Cum. IAQ before	277,786	74,591	235,753	11,752	70,781	N/D	1609	15,096	41,217	20,617	21,657	354,005
	Cum. IAQ during	262,611	21,831	311,684	1681	157,662	N/D	0	0	8617	6558	6792	202,463

Table 7. *Cont.*

		Data Logged											
Category	**Variable**	**CS1**	**CS2**	**CS3**	**CS4**	**CS5**	**CS6**	**CS7**	**CS8**	**CS9**	**CS10**	**CS11**	**CS12**
Bedroom	Mean T before	20.84	20.58	21.11	18.08	25.32	N/D	19.43	N/D	18.65	20.62	19.11	20.48
	Mean T during	20.75	21.26	23.51	19.21	24.84	N/D	20.04	N/D	19.06	20.90	19.83	21.10
	Max T before	24.15	22.10	26.08	21.65	28.20	N/D	20.88	N/D	22.00	22.40	21.80	24.35
	Max T during	23.85	22.30	26.55	21.66	27.35	N/D	20.90	N/D	22.20	22.20	21.40	24.00
	Min T before	18.05	19.80	19.00	14.90	23.10	N/D	18.00	N/D	15.42	19.50	16.23	17.90
	Min T during	18.70	19.85	20.55	17.15	23.30	N/D	18.40	N/D	15.30	19.55	17.90	19.00
	Mean RH before	75.79	56.65	69.83	81.30	49.14	N/D	40.02	N/D	71.20	49.38	56.76	75.61
	Mean RH during	73.70	54.10	53.33	87.30	53.18	N/D	42.21	N/D	70.31	50.29	53.75	70.14
	% comf. h before	11%	92%	60%	21%	99%	N/D	27%	N/D	14%	83%	34%	5%
	% comf. h during	0%	99%	100%	35%	100%	N/D	49%	N/D	27%	96%	45%	53%
	% outd. comf. h + IEQ before	0%	33%	46%	54%	7%	N/D	46%	N/D	4%	54%	65%	0%
	% outd. comf. h+IEQ during	0%	0%	0%	80%	0%	N/D	100%	N/D	50%	100%	100%	0%
	Mean IAQ before	2305	1286	1539	753	1312	N/D	912	N/D	1437	1224	1208	2263
	Mean IAQ during	2441	1156	1695	653	1505	N/D	841	N/D	1316	1232	1071	1722
	Cum. IAQ before	340,679	45,684	160,516	0	14,810	N/D	3279	N/D	119474	85,026	54,424	354,005
	Cum. IAQ during	367,732	0	189,187	0	99,268	N/D	0	N/D	81502	71,840	17,150	202,463

Table 8. Comparison of survey and sensor-logged data.

	Parameter Compared	PRE	PRE	DL	DL	PRE	PRE	DL	DL	PRE	PRE	DL	DL	PRE	PRE	PRE	DL	DL	DL	PRE	PRE	DL	DL	PRE	DL
		CS1	**CS2**	**CS1**	**CS2**	**CS3**	**CS4**	**CS3**	**CS4**	**CS5**	**CS6**	**CS5**	**CS6**	**CS7**	**CS8**	**CS9**	**CS7**	**CS8**	**CS9**	**CS10**	**CS11**	**CS10**	**CS11**	**CS12**	**CS12**
Starting Data	**Dwelling characteristics** General upkeep	G	G			G	P			M	G			M	P	M				M	M			P	
	Household characteristics Occupation density Incr. occupation	A	VG	++	+	VG	G	+++	++	A	VG	+	+	G	G	A	++	++	+	A	VG	++	+	P	=
	Potential of passive measures Living room Bedroom			= =	= -			= -	+ +			- -	N/D N/D				+ +	= N/D	= +			+ +	+ +		= =
Iaq	**General environmental quality** Air quality Ventilation frequency	G A	G A	++	=	VG A	G G	=	=	M A	VG A	+	=	VG A	G G	G G	=	=	=	VG G	P A	=	=	P G	=
	IAQ **Living room** **Bedroom**	P P	M M	P P	M M	P P	G G	P P	G G	M P	N/D N/D	P P	N/D N/D	VG A	VG N/D	G PP	VG A	VG N/D	VG A	M M	M M	M M	M M	P P	P P
Power Consumption	**Habits** Habits entailing power consumption			+	++			=	+			+	++				++	+++	++			++	=		=/+
	Facilities (Consumption) (Appliances/DHW/heating) Electricity Natural gas			++ +	= =			+	= =			++	=				=/+ =/+	+++ +/=	=/+ =/=			++ +	+ =/+		=
	Energy saving strategies			P	VP			P	VP			VP	R				VP	VP	A			VP	A		VP
	Fuel vulnerability (% income for power)	M	+	P	=	N/D	+	M	=	M	+	A	=	M	M	A	=	+	+	S/D	+	A	=		=
	Consumption: Electricity Natural gas			+ -	- +			+	=			+	N/D				- N/D	+ -	+ N/D			+	+		+
Comfort	**Comfort-adaptation:** Comfort? Does adaptation entail power consumption?	M	G	=	=	G	P	=	+	G	G	=	=	G	M	M	=	=	=	G	M	=	=		=
	Air comfort: Living room Bedroom	VG VP	VG VG	VG VP	VG VG	VP G	A M	VP VG	A A	VG VG	N/D N/D	VG VG	N/D N/D	VG A	VG N/D	G M	VG A	VG N/D	VG A	VG VG	VG A	VG VG	VG A	VG VP	VG G

Six-point scale where: VP: very poor; **P**: poor; **M:** mediocre; **A:** acceptable, adequate; **G:** good; **VG:** very good; **N/D:** no data, nothing reported. NOTE: Depending on the nature of the variables, in some categories their scale was reduced to 5 or 4 points. For increased use or consumption, the options applied were: -: less; =: the same; +: greater;++: much greater; +++: very much greater. PRE: Pre-lockdown; DL; during lockdown.

5. Analysis and Discussion of Results

5.1. Mixed Method

With the mixed method, data from two distinct sources (the surveys conducted prior to and during COVID-19 lockdown and the temperature, relative humidity and indoor air quality data logged by sensors in those same periods) could be analysed jointly. The analysis aimed essentially to obtain a deeper understanding of the impact of lockdown and concomitant 24/7 occupation on indoor environmental quality and power consumption in dwellings. More specifically, in addition to looking into the periods before and during of the state of emergency [5], the study aimed to compare users' subjective perception in those variables to the instrumental data recorded.

Therefore, the joint analysis of the factors addressed, including initial weather, housing quality and occupation variables, as well as the comparison of power consumption, thermal comfort, humidity and air quality in the two periods studied, had a dual purpose, as premised in the methodological triangulation. That approach [84,85] pursues two essential objectives: (1) enrichment of the research itself by addressing data from two distinct sources; and (2) enhancement of research quality control and therefore of the reliability if the results [98]. In this case the reliability of the results may also provide insight into households' subjective perception of the parameters measured by the sensors, namely the comfort, air quality and power consumption.

Merging the quantitative (sensor-logged) and qualitative (surveys with open questions and visits to dwellings early in the process) data affords a fuller view of any given circumstance, in this case COVID-19 lockdown in social housing in Madrid, from different perspectives, generating deeper overall understanding of the situation [99], along with methodological validation [85].

5.2. Outdoor Conditions

According to weather station records, weather conditions immediately prior to lockdown were characteristic of late winter and early spring (Table 6 and Appendix A). Data before lockdown: 36-degree days, mean temperature 14 °C, with a high T of 24 °C and a low of 3 °C; 14% of comfort hours. Data during lockdown: 46-degree days, mean temperature 12 °C, with a high of T 22 °C and a low of 4 °C; 3% of comfort hours. Consequently, the comparison of the before and during lockdown situations was essentially unconditioned by the weather.

5.3. Occupation Density

The effect of the sudden change from presence at home from 11 h to 21 h per day [86,100,101], to practically 24 h/7 d a week [94] on the case study dwellings varied depending on the starting data (Table 8). Dwellings CS2, CS3 and CS6 scored the highest at the outset, whilst the values for CS1 were acceptable. Those four flats were generally well kept up and exhibited fairly comfortable occupation densities of around 0.02 p/m^2 both before and during lockdown. Density rose most steeply in CS3 especially, by 54.17%, followed by CS1, CS4, CS7, CS8 and CS10, with values ranging from 30% to 45%. Occupation density rose in the lockdown period studied by less than 30% in the other six dwellings. The last starting data variable was the potential of passive measures. The values observed showed that CS4, CS7, CS10 and CS11 started with the most suitable behaviour and that lockdown had an adverse effect on CS5 in that regard. The data for the remaining cases were either incomplete or denoted no significant variation relative to the week prior to lockdown.

5.4. Power Consumption

The values for the during-lockdown consumption parameters studied [86,102] differed from one dwelling to another (Table 6 and Appendix A). Electric power consumption relative to a standard value rose to a greater or lesser percentage during lockdown in 10 of the 12 dwellings, with CS7 and CS1 as the exceptions. In the three dwellings where it was monitored, natural gas consumption rose in CS2 and declined in CS8 and CS1. The ratio between consumption and heating degree days was clearly greater before than during lockdown in all three. User-reported power consumption (Table 4) was generally consistent with the patterns identified from the findings logged by the sensors, attesting to users' conscious association of their behaviour to power consumption, either out of necessity, ingrained habit or environmental conviction. A number of variables informed the power consumption category (Table 8). Firstly, habits prior to or changed under lockdown circumstances affected consumption attributable to appliances and devices used in the dwelling and DHW and heating facilities. Depending on each household's attitude, energy saving strategies may have been implemented during lockdown with a view to countering consumption. Vulnerability data, in turn, afforded insight into consumption prior to and during lockdown, serving as a control to better understand user-reported values for the aforementioned variables. Consumption tended to rise most intensely in CS8, followed by CS2, CS6, CS7, CS9 and CS10. That finding was consistent with user-reported data, where CS8 claimed a much greater increase in power consumption during lockdown than in the pre-lockdown period than the other dwellings. Consumption also rose in CS1, CS5 and CS10, although less steeply relative to earlier values, as well as in CS3 and CS11, although to a lesser extent, and barely at all in CS7 and CS9. According to the sensor-logged data, power consumption rose in CS1, CS3, CS5, CS8, CS9, CS10, CS11 and CS12, matching the survey results almost perfectly. Although CS2 reported a rise in natural gas consumption, on the whole the dwellings were more cautious in this regard, whilst CS1 and CS8 claimed to have lowered their consumption.

In terms of vulnerability, the least favourable conditions were reported by dwellings CS1, CS2 and CS8.

5.5. Thermal Comfort

Thermal comfort (determined by air humidity and temperature [29,86,101]) generally improved in the living room and bedroom, although to a greater or lesser extent depending on the dwelling studied (Figure 4). The sole exception was dwelling CS1, where fewer comfort hours were logged in the bedroom during lockdown. Although fewer outdoor comfort hours were observed during lockdown, no data were collected on the potential of passive measures in the CS1, CS3 or CS12 living rooms, whilst the value declined in CS2 and CS5 and rose in CS4 and CS7. CS9, CS10 and CS11 all drew advantage from outdoor comfort hours during lockdown, whilst CS8 capitalised on outdoor comfort to ensure a good IEQ before and during lockdown (Table 6 and Appendix A). The data for bedroom comfort hours during lockdown indicated no records for CS1 or CS12; declines in CS2, CS3 and CS5; rises in CS4 and CS7; and use of outdoor comfort hours by CS7, CS10 and CS11. The subjective data on perceived comfort (Table 5), however, were not fully consistent with those findings, for a number of possible reasons. Firstly, some respondents answered the questions on thermal comfort as an average for the two rooms instrumented. For instance, if the living room, used during the day and was highly comfortable but the bedroom the contrary, the overall perception conditioned the thermal comfort reported. In a way, however, such responses may be explained both by the habits acquired during lockdown as well as by the disparity in the data structure: comfort parameters were measured room-by-room whereas the survey questions referred to overall perception.

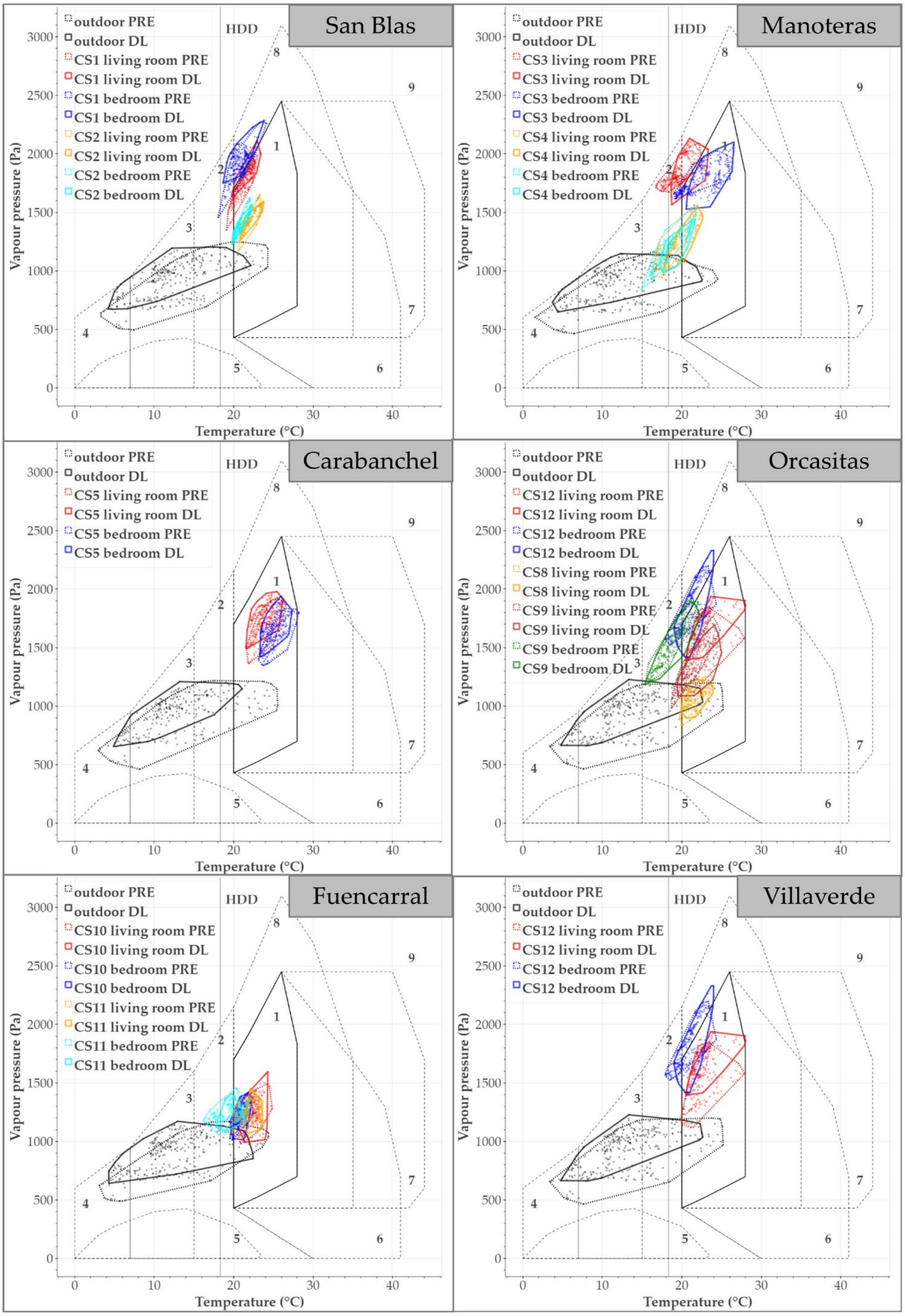

Figure 4. Givoni charts by neighbourhoods. Sensor-logged data.

The comfort and adaptation category (Table 8), in turn, was analysed with two survey variables, namely perceived temperature and the measures adopted to counter possible discomfort, and whether or not they entailed power consumption. Those variables were compared to the sensor-logged indoor temperature and relative humidity readings in living rooms and bedrooms. On the whole, perceived comfort was consistent with in situ measurements in the dwellings with the most favourable conditions, CS2, CS5, CS7 and CS10. Some discrepancies were nonetheless observed between perceived and objectively measured comfort. CS3 had the most optimistic dwellers, while among the optimists in general users reporting indoor comfort as an average of the two rooms prevailed. For instance, whilst CS1 reported the living room to be very comfortable and the bedroom not at all, perception was averaged for the two rooms in CS4, where the value assigned was 'acceptable' for both, and in CS9 and CS12. The pessimistic users, in turn, living in CS2, CS4, CS5, CS8, CS10 and CS11, reported lower comfort levels than indicated by the observed ranges of temperature and RH. Lastly, passive comfort revealed the initial situation to be more favourable for CS4, CS7, CS10 and CS11 and lockdown to have had an adverse effect on CS5. The data for the remaining cases were either incomplete or showed no significant change relative to the week prior to lockdown.

5.6. Air Quality

Indoor air quality [29,86,101,103], expressed here as mean and cumulative values, improved in the living room during lockdown except in CS3 and CS10 (mean value). Indoor air quality in the bedroom improved in CS2, CS7, CS9, CS11 and CS12, but not in CS1, CS3, CS5 and CS10. Improvements in air quality did not necessarily translate into good or acceptable quality, which is an indication that ventilation practice was insufficient on the whole (Table 6 and Appendix A). The greatest discrepancies between user perception (Table 4) and sensor-logged data were observed in connection with indoor air quality. Here, also, average perception for the two rooms was sometimes reported, despite wide differences (also related to daytime/night-time behaviour patterns). Nonetheless, some users proved to be optimistic in their perception of 'acceptable' air quality whilst other households were pessimistic, scoring quality as lower than the standard-compliant values actually measured. The two variables on which perceived indoor environmental quality (Table 8) and more specifically air quality were based were perceived air quality and comparative ventilation frequency. When the two variables were assessed jointly, the dwellings with the highest scores for ingrained household practice were CS4, CS7, CS8, CS9 and CS10. A comparison with the sensor-logged data revealed the same pattern in all but CS10. Nonetheless, whereas those patterns generally referred to living room ventilation, air quality was lower in the bedrooms on the whole. During lockdown, the dwellers in CS1 and to a lesser extent CS5, where starting values were not very good, reported improving their habits during lockdown. Further to the sensor-logged data for air quality, however, CS1 and CS2 practice did not improve enough for IEQ to be classified as anything other than poor or mediocre, respectively. In contrast, the survey scores were the lowest in CS11 and CS12, where no substantial improvements were forthcoming judging from the scant variation in their ventilation routines. Those findings were consistent with the sensor-logged data. The dwellers in CS3 and CS10, in turn, were much more optimistic about indoor air quality and ventilation practice than denoted by the CO_2 concentration values. The perception of both air quality and ventilation practice, then, varied widely from dwelling to dwelling.

5.7. Goals and Limitations

An important goal addressed in this study has been to unveil and validate differences in IEQ and energy consumptions patterns before and during COVID-19 through the mixed approach. To determine the goal at the time, the questionnaires focused on determining the following: households' characteristics and habits; power-consuming facilities; indoor environmental quality; comfort and adaptation; energy savings strategies and use of renewables. This approach allowed for the integration of qualitative information (from the open-ended questionnaires and eventual brief interviews when installing the equipment) into the quantitative results (from the monitoring campaign) on IEQ and energy use. This study also provided objective data on the energy situation of the studied cases, useful for potential studies and the enrollment in energy rehabilitation programs (such as the European Regional Development Fund (ERDF) [104]).

Three main limitations related to this type of study were addressed in relation to generalization, technology and indoor air quality. First of all, due to a mixed nature, and the number of case-studies, the representativeness of the results is not possible. In addition, as far as the results of the analysis are related to contextual variables (climate, occupant profile, lifestyle, cultural background), it contributes to bear in mind all of them before comparing with other studies. Other limitations came from some technological concerns: on the one hand, the very nature of online surveys, for instance, which require the availability of digital resources, internet connection and a minimum of knowledge to understand and self-complete them successfully and on the other hand, the cost, maturity and adaptability of the technical platform, and the tools delivered for data collection. Some limitations came from problems related to the monitoring campaign: beyond the lack of Internet connection, network stability and capacity, lack of power, interferences, etc., were the main difficulties that may be encountered. For a successful monitoring campaign, these constraints require the effectiveness of data collection methods and user selection and commitment. However, this work demonstrated the use of different types of data in the analysis can help to overcome these problems. Finally, in this study, indoor air quality has been defined only with the CO_2 parameter since with only this variable we inferred ventilation patterns (determinant aspect in COVID-19 lockdown). VOCs [94,105], radon [106,107] and fungi [108], which would be desirable parameters to collect, were not measured in favour of respecting the social and physical distancing and restricted mobility required by the Spanish Royal Decree on the State of Alarm. In addition, the opportunity to analyze such an abrupt and unusual event (confinement) elicited the haste in making decisions about measurements and user-centered techniques, the difficulty of access to housing, as well as the availability of resources and households and their willingness to collaborate in what was seen as a unique and unprecedented extreme situation.

6. Conclusions

Merging the quantitative and qualitative data affords a fuller view of any given circumstance, along with methodological validation. The findings for the 12 case studies revealed different starting conditions for variables such as household composition (from singles to large families) and very diverse dwelling characteristics (general upkeep, envelope and window quality), as well as differences in initial predisposition depending on orientation (determining sunlight) and height relative to the building as a whole.

Such wide inter-dwelling differences, even in flats in one and the same building, partially conditioned household risk of discomfort. This category of variables referred to initial issues and the degree to which each household could solve them with different passive strategies such as adaptation or acclimation [109] or using heating with the concomitant power consumption [51].

In turn, situations more closely related to indoor environmental quality [94,110] and to power consumption patterns before and during lockdown changed in keeping with starting conditions, occupation density (8/12 case studies increase occupancy density by more than 25 percent) and household behaviours during lockdown (11/12 case studies improve thermal comfort; 10/12 improved air quality but did not necessarily translate into sufficient ventilation practices; air quality was lower in the bedrooms on the whole; only 4/12 case studies use the potential of passive measures). Behavioural patterns that depended on circumstances and specific household needs (such as the presence of minors or dependent persons or higher temperature comfort demands) [39] as well as on user commitment to efficient energy use [111] were observed. Only one household adopted energy savings strategies that differed from the other eleven, for instance.

The households with clearly less favourable starting conditions were the ones, generally speaking, who adopted more measures to mitigate discomfort or take better advantage of passive strategies [112] such as natural ventilation and lighting and the ones, much to their regret, and only where strictly necessary, resorted to heating to attain the desired comfort levels [51].

Most households were also observed to distinguish between daytime and nighttime in an attempt to minimise consumption, ventilating only in empty rooms to conserve thermal comfort as far as possible.

Power consumed for electrical appliances [16] in keeping with household needs was governed by the everyday tasks performed by users and the number of people present in each dwelling. The literature on this subject [36,37] confirms that power consumption rose as a rule during lockdown, (10/12 case studies increased electric power consumption), irrespective of household vulnerability, with the least advantaged applying more savings measures and resorting more intensely to passive strategies, in particular in pursuit of comfort, behaviours in fact directly associated with vulnerability and fuel poverty during lockdown [72].

The conclusion that can consequently be drawn is that although starting conditions differed widely, household composition, habits and the way daily activities were performed [113], and therefore power consumption, also played an active role in the end result. Nonetheless, none of these dwellings were fitted with renewable energy-fuelled generation systems that might have limited their dependence on fossil fuel power and rendered dwellings more self-sufficient in terms of power production, at least for a certain percentage of their daily demand. Such arrangements would be desirable not only in response to calls for decarbonation and energy transition, but especially in the present lockdown-induced context of uncertainty and contingency around worldwide resources in general and buildings and their facilities in particular [114,115].

This contribution may also suggest technological and human-centered implications and housing interventions in several ways. Firstly, in the generation of rapid guides or good practices compatible or even included in contingency plans that require interventions in the home or follow-ups considering various data collection techniques. Secondly, technological advances in monitoring could be improved considering this extreme situation that involves people to remain inside due to lockdowns. Third, programs of households' enrollment, awareness, housing digitalization and energy/IEQ training could be interesting or relevant, even more when people stay at home for a long and uncertain period. Finally, fully immersed in the renovation wave and promotion of the rehabilitation of the European Green Deal and other initiatives also at the national level, it is important to consider digitization and the user engagement proactively in these actions, as well as the resilience of homes in deep rehabilitation, and not only covering energy issues. The COVID-19 pandemic has retaken the relevance of IEQ. All of these aspects approach housing to greater self-sufficiency and energy independence, an adequate energy and digital transition, and better well-being and health for their residents, which results in a greater return on investment of these actions at a social and economic level.

Author Contributions: Conceptualization, F.d.F. and T.C.-V.; data curation, F.d.F. and T.C.-V.; formal analysis, F.d.F. and T.C.-V.; funding acquisition, I.O.; investigation, F.d.F. and T.C.-V.; methodology, F.d.F., T.C.-V. and M.Á.N.-M.; project administration, I.O.; resources, F.d.F., T.C.-V., C.A., F.M.-C., I.O. and M.Á.N.-M.; software, F.d.F., T.C.-V. and M.Á.N.-M.; supervision, F.d.F., T.C.-V., C.A., F.M.-C., B.F., I.O. and M.Á.N.-M.; validation, F.d.F. and T.C.-V.; visualization, F.d.F. and T.C.-V.; writing—original draft, F.d.F. and T.C.-V.; writing—review and editing, F.d.F., T.C.-V., C.A., F.M.-C., B.F., I.O. and M.Á.N.-M. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki. In addition, the original questionnaire was approved by the Ethics Committee of Consejo Superior de Investigaciones Científicas (CSIC), approval number 057/2020, on 30 April 2020.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data are not publicly available due to ethical reasons.

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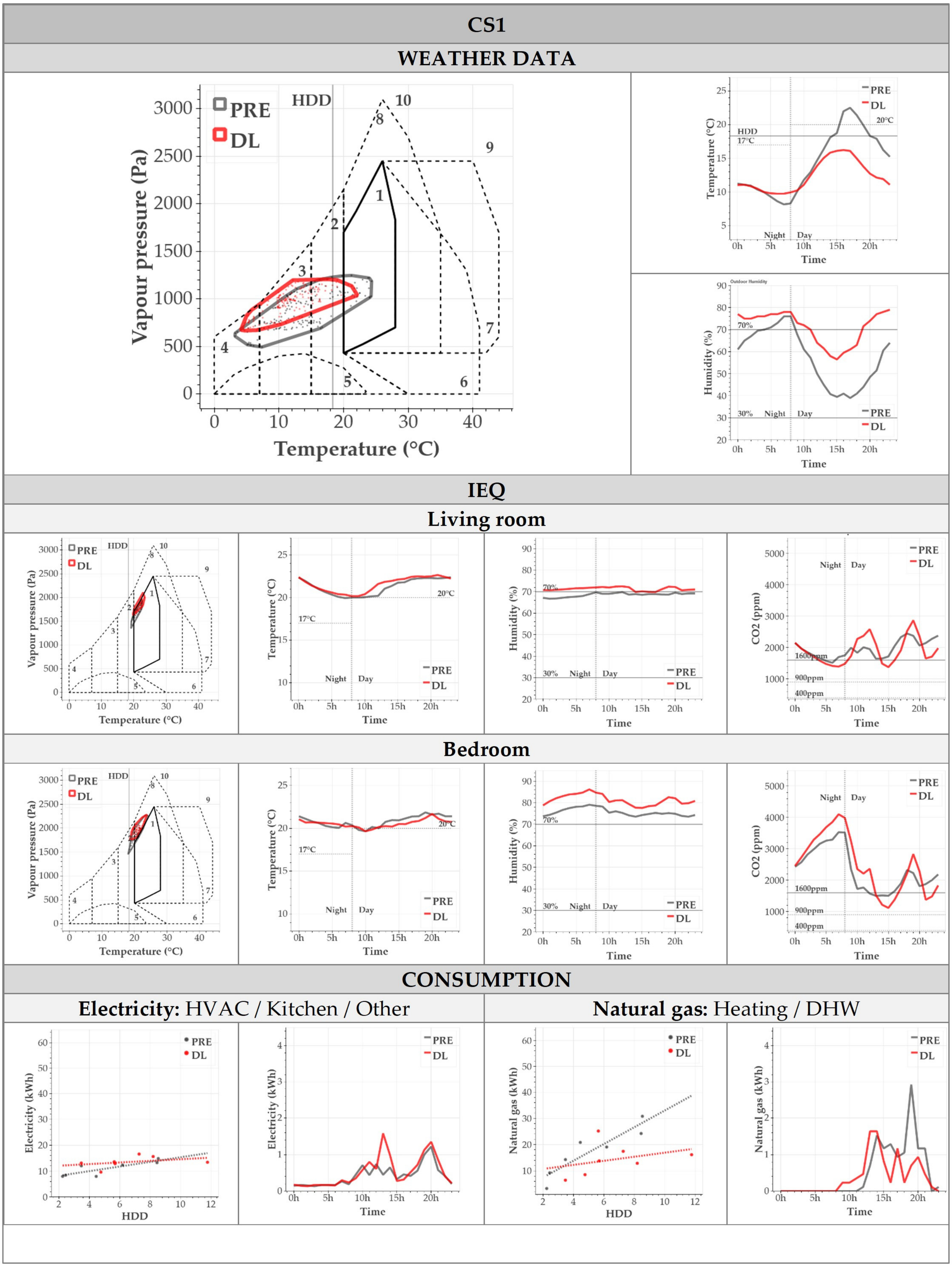
Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

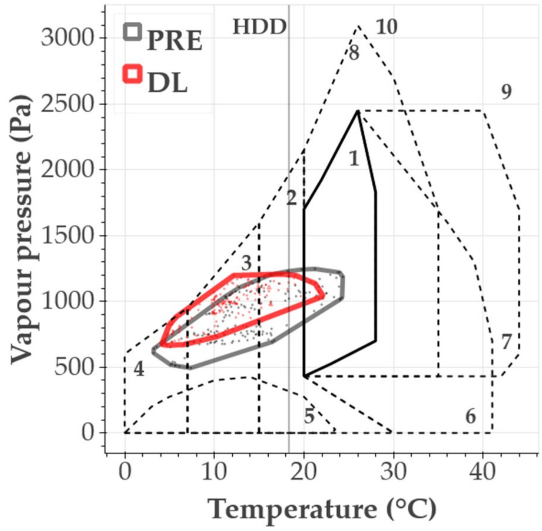
PRE	pre-lockdown
DL	during lockdown
IEQ	indoor environmental quality
DHW	domestic hot water
HVAC	Heating, ventilation and air conditioning
HDD	heating degree days
N/D	no data

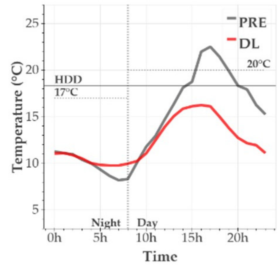
Appendix A

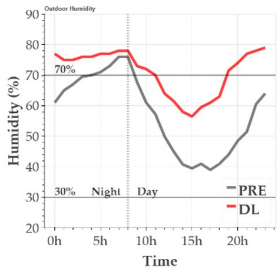

CS1
WEATHER DATA
PRE
DL
HDD
Vapour pressure (Pa)
Temperature (°C)
Temperature (°C)
Time
Night
Day
20°C
17°C
Humidity (%)
Outdoor Humidity
70%
30%
IEQ
Living room
CO2 (ppm)
1600ppm
900ppm
400ppm
Bedroom
CONSUMPTION
Electricity: HVAC / Kitchen / Other
Natural gas: Heating / DHW
Electricity (kWh)
HDD
Natural gas (kWh)

CS2

WEATHER DATA

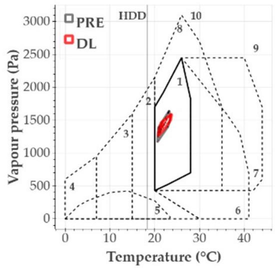


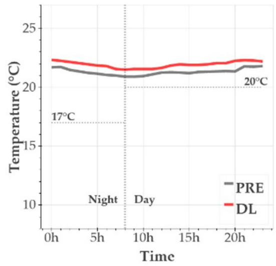


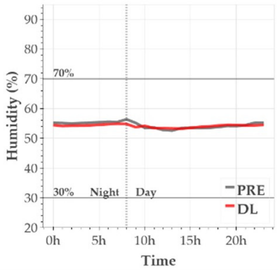


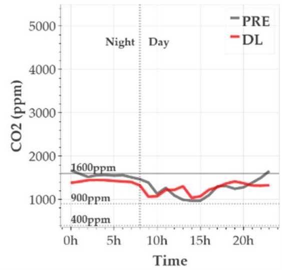
IEQ

Living room

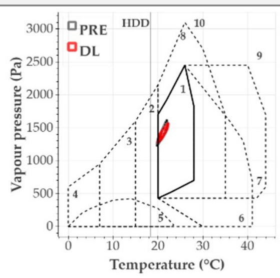


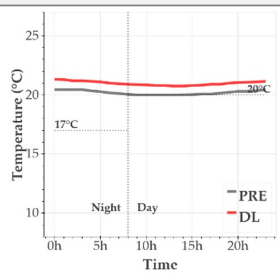


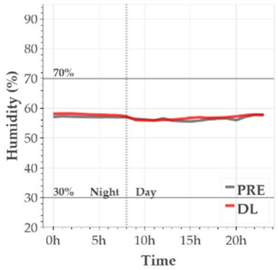


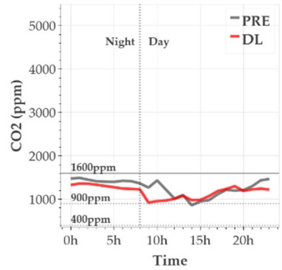


Bedroom



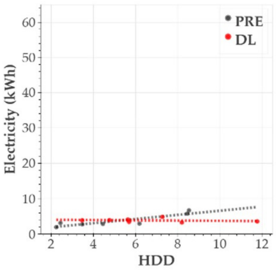


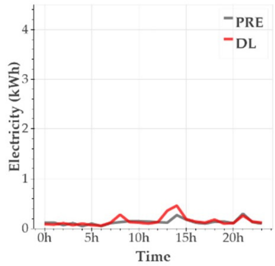




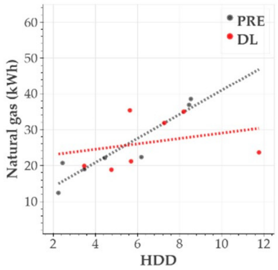
CONSUMPTION

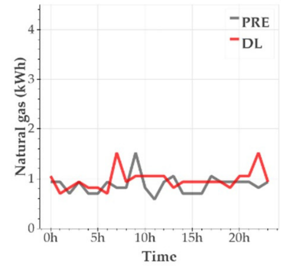
Electricity: HVAC / Kitchen / Other





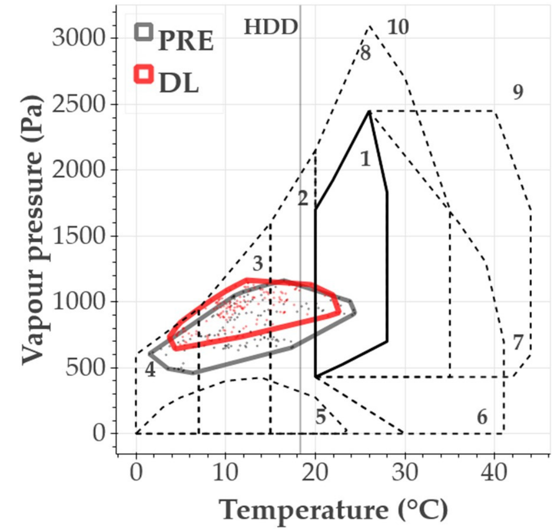
Natural gas: Heating / DHW

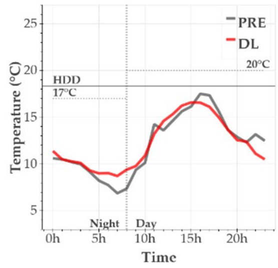


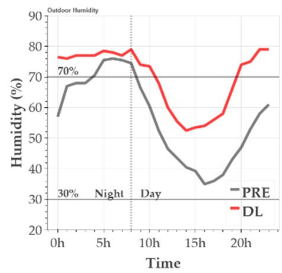


CS3

WEATHER DATA

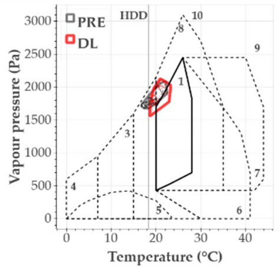


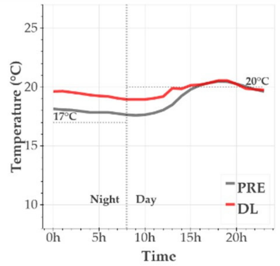


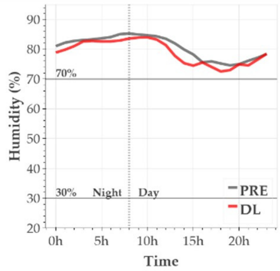


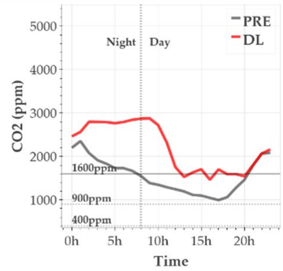
IEQ

Living room

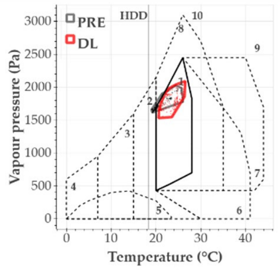


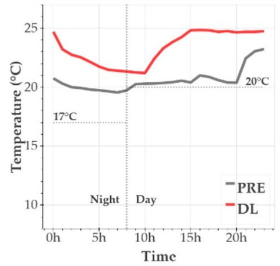


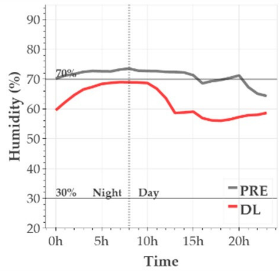


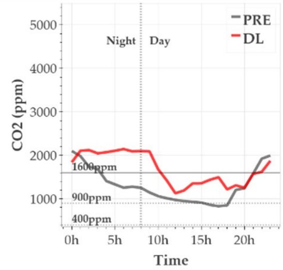


Bedroom





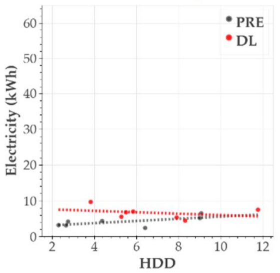


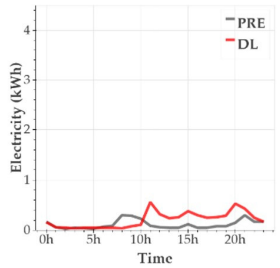


CONSUMPTION

Electricity: HVAC / Kitchen / Other

-





CS4

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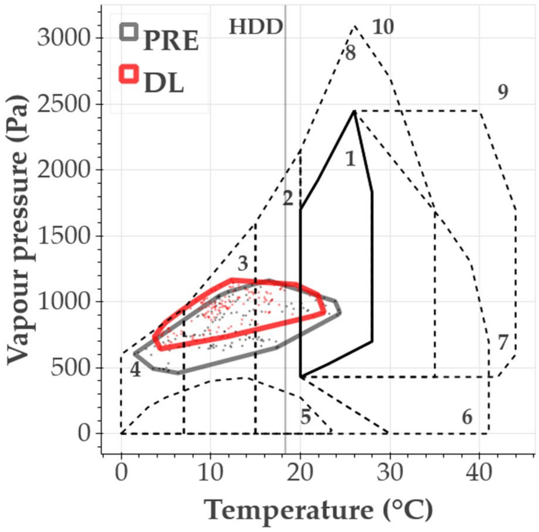
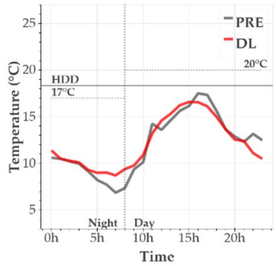
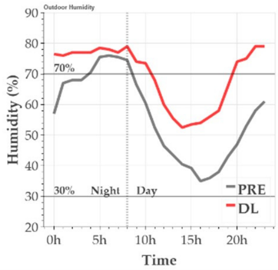
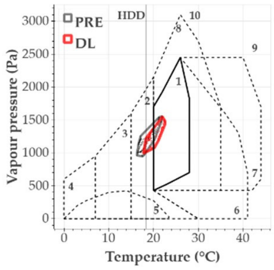


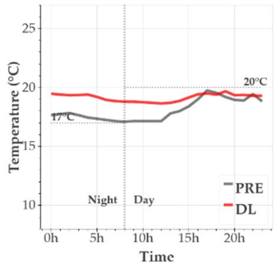


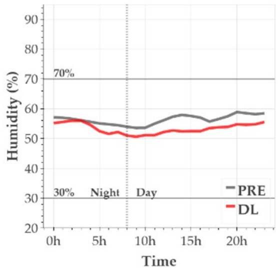


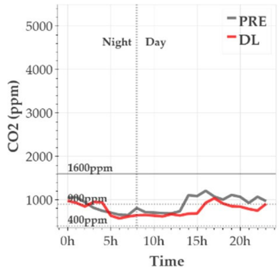
IEQ

Living room

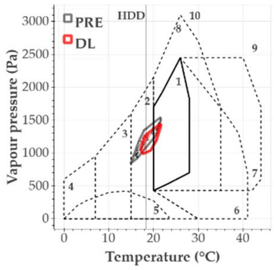


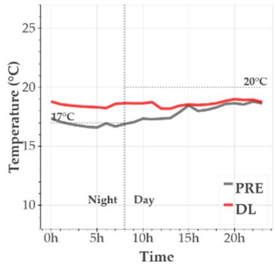


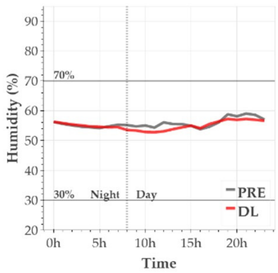


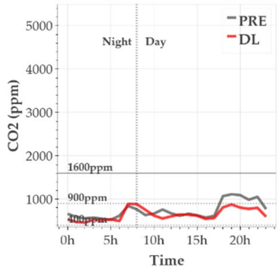


Bedroom



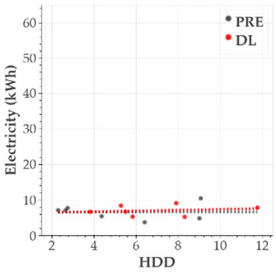


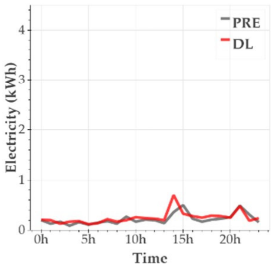




CONSUMPTION

Electricity: HVAC / Kitchen / Other





Natural gas: Heating / DHW - Not monitored

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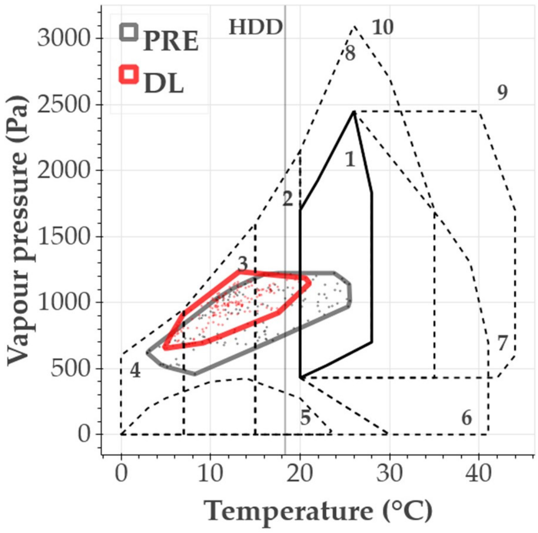
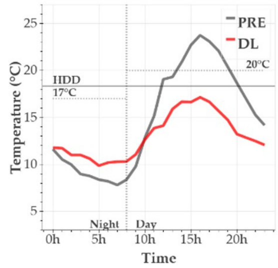
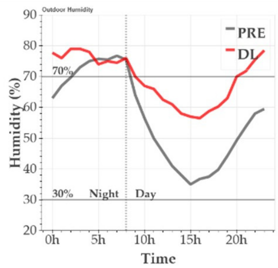
CS5

WEATHER DATA

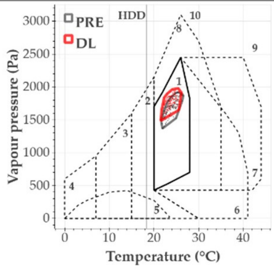


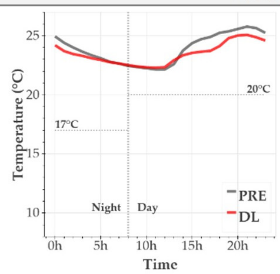


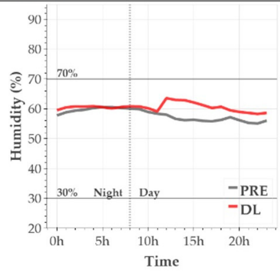


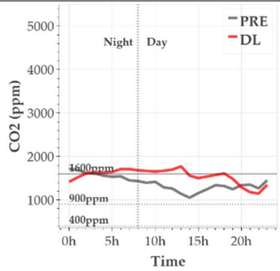
IEQ

Living room

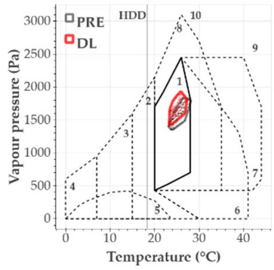


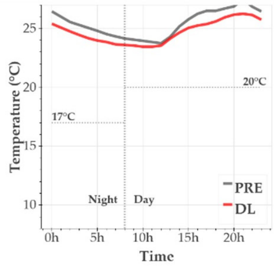


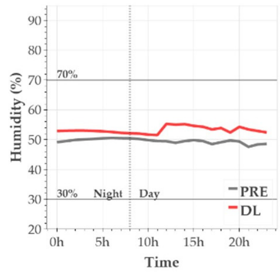


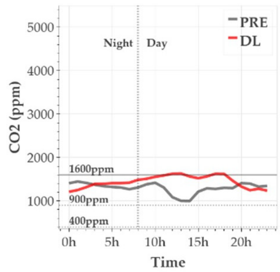


Bedroom

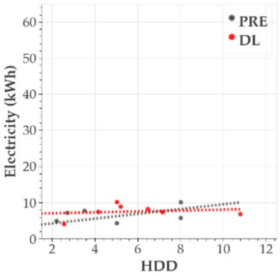
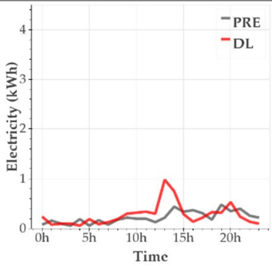








CONSUMPTION

Electricity: HVAC / Kitchen / Other		**Gas-oil:** Heating / DHW - Not monitored	
		-	-

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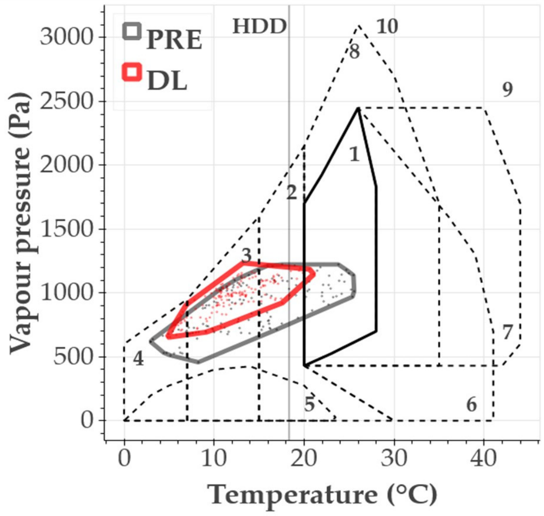
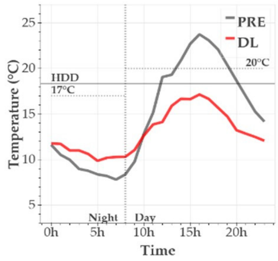
<tr><td colspan="2" rowspan="2">
</td><td colspan="2">
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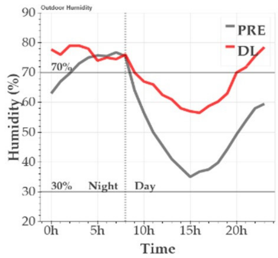
<tr><td colspan="2">
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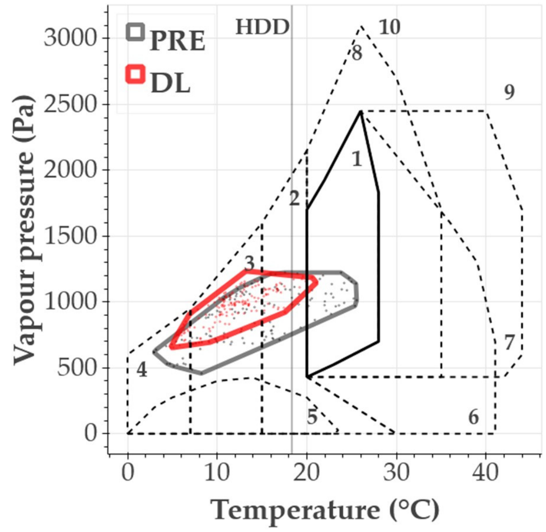
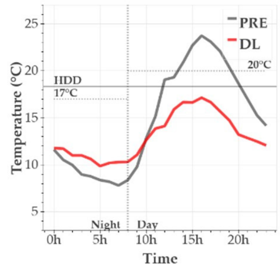
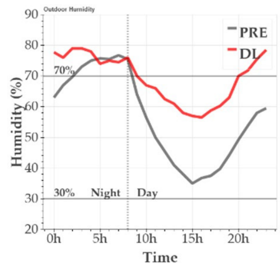
CS7

WEATHER DATA

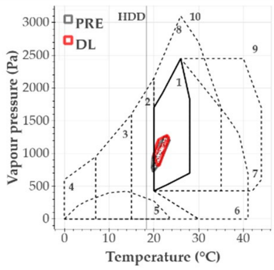


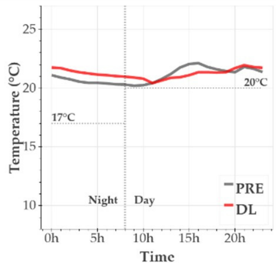


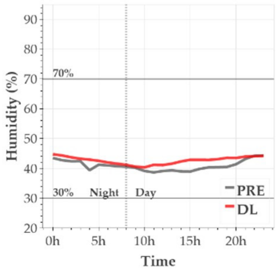


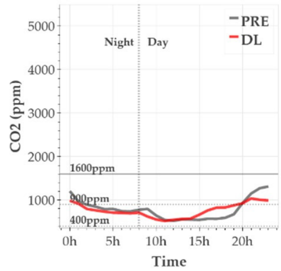
IEQ

Living room

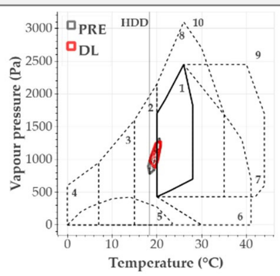


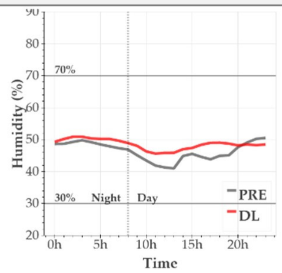


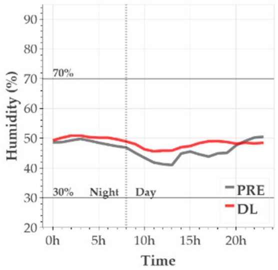


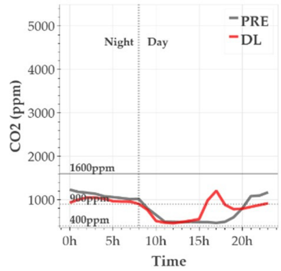


Bedroom



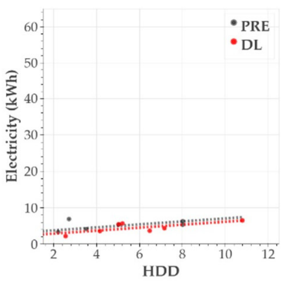


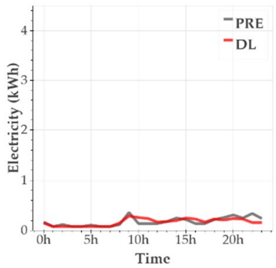




CONSUMPTION

Electricity: HVAC / Kitchen / Other





Natural gas: Heating / DHW - Not monitored

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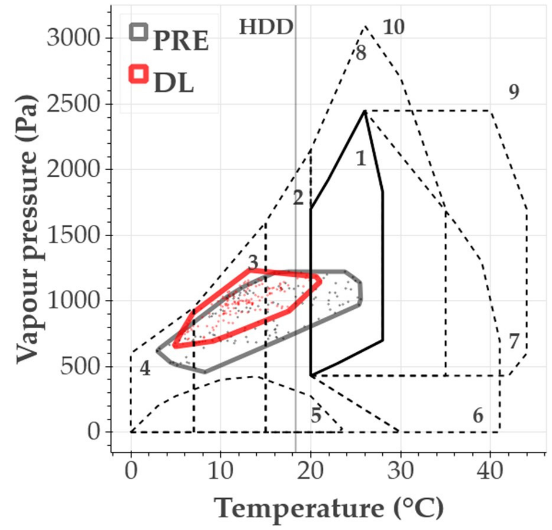
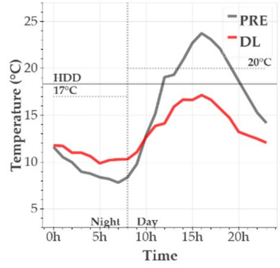
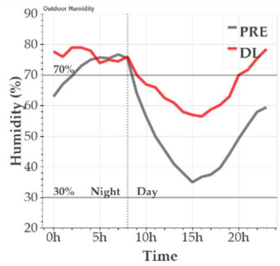
CS8

WEATHER DATA

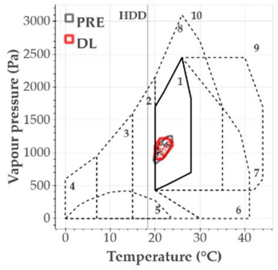


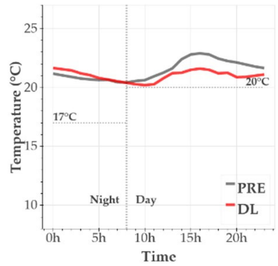


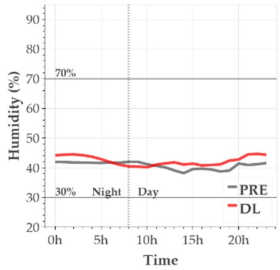


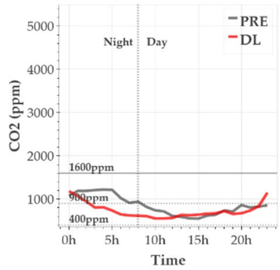
IEQ

Living room







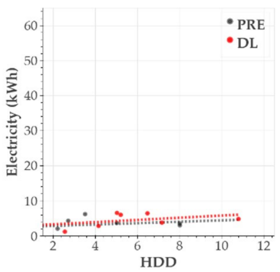


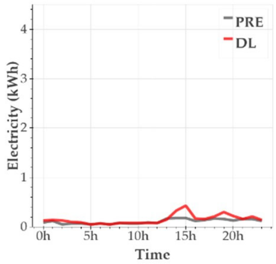
Bedroom

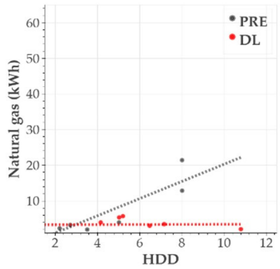
N/D	N/D	N/D	N/D

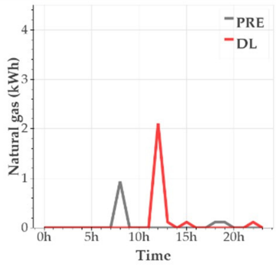
CONSUMPTION

Electricity: HVAC / Kitchen / Other	**Natural gas:** Heating / DHW



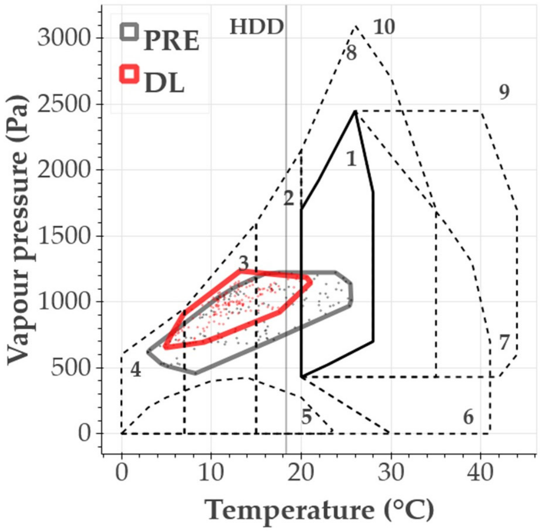


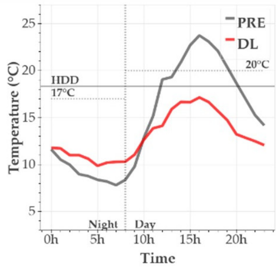


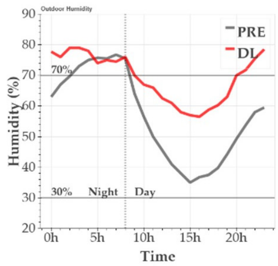


CS9

WEATHER DATA

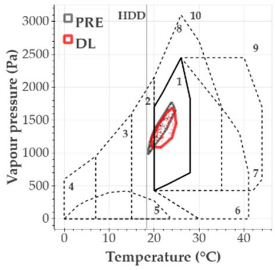


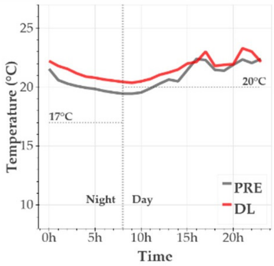


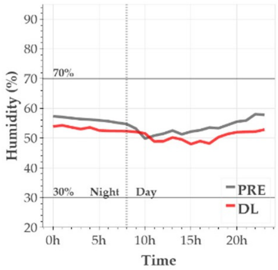


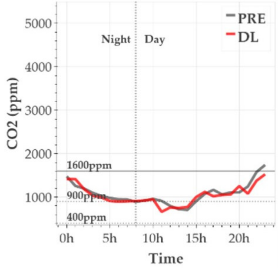
IEQ

Living room

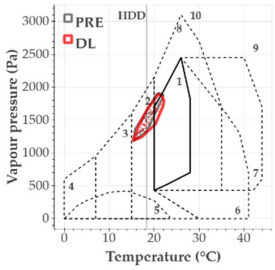


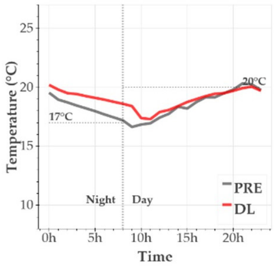


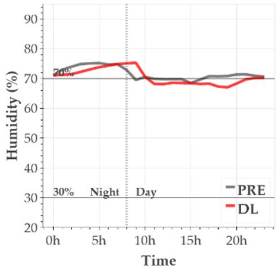


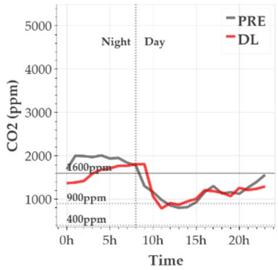


Bedroom



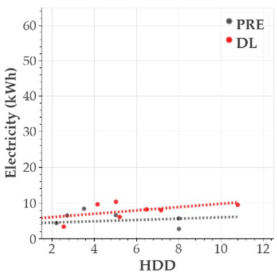


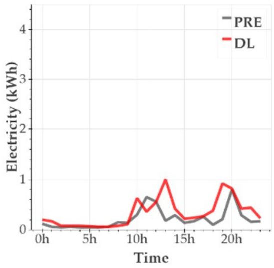




CONSUMPTION

Electricity: HVAC / Kitchen / Other





Natural gas: Heating / DHW - Not monitored

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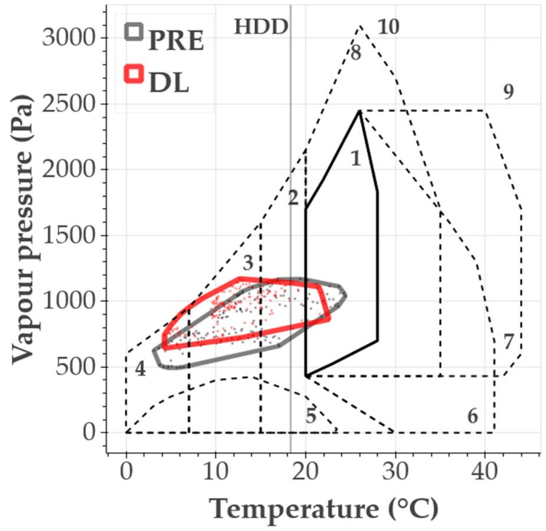
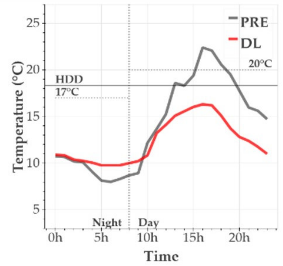
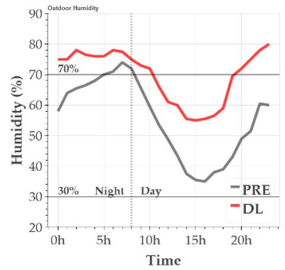
CS10

WEATHER DATA

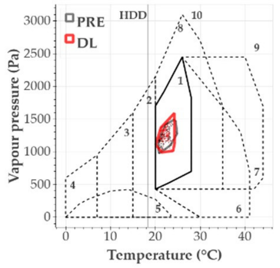


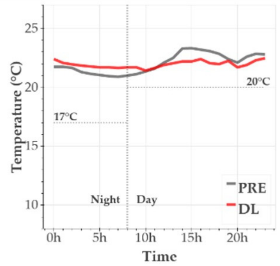


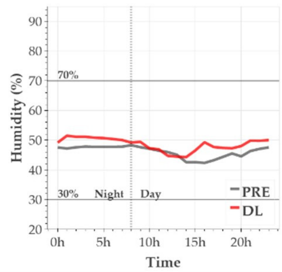


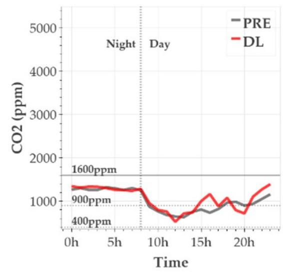
IEQ

Living room

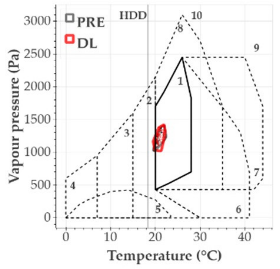


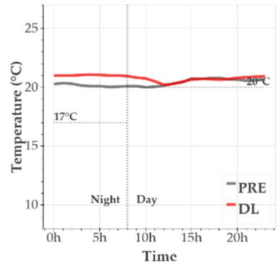


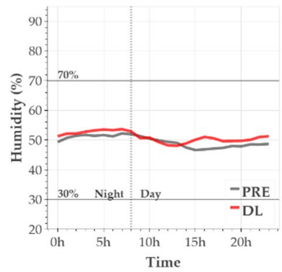


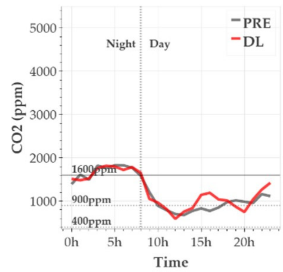


Bedroom



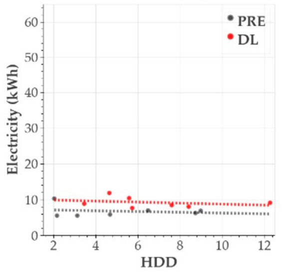


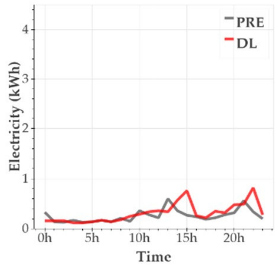




CONSUMPTION

Electricity: HVAC / Kitchen / Other





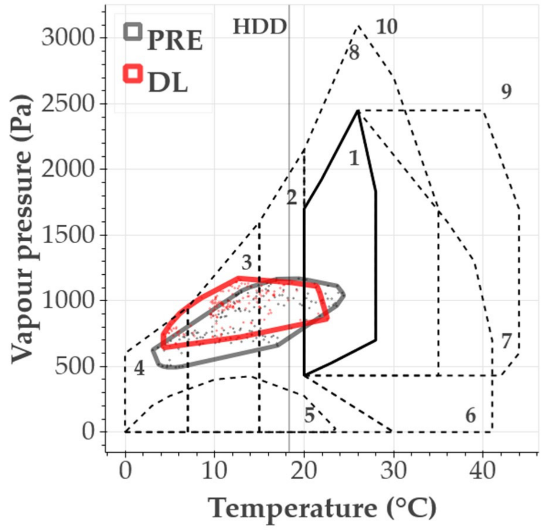
Natural gas: Heating / DHW

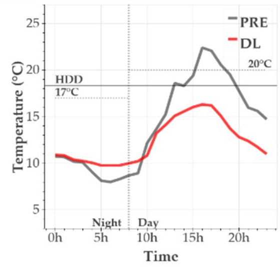
N/D

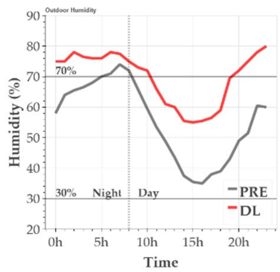
N/D

CS11

WEATHER DATA

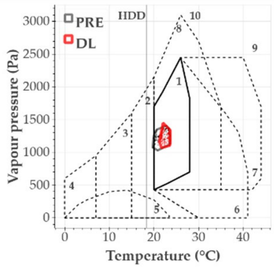


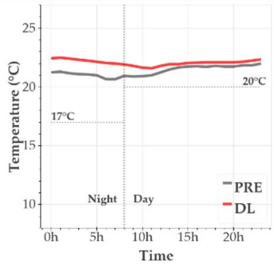


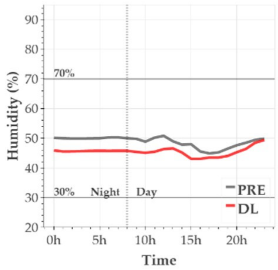


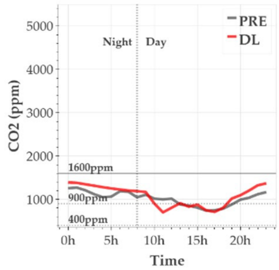
IEQ

Living room

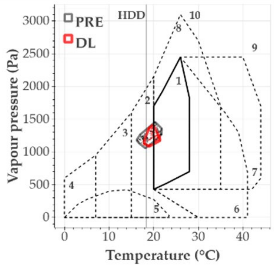


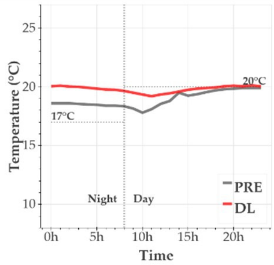


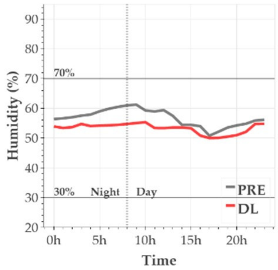


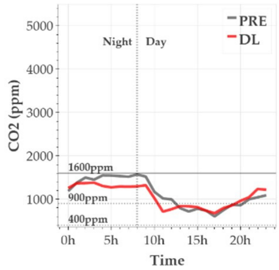


Bedroom



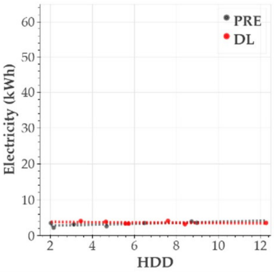


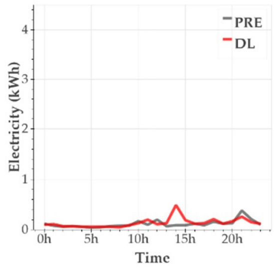




CONSUMPTION

Electricity: HVAC / Kitchen / Other





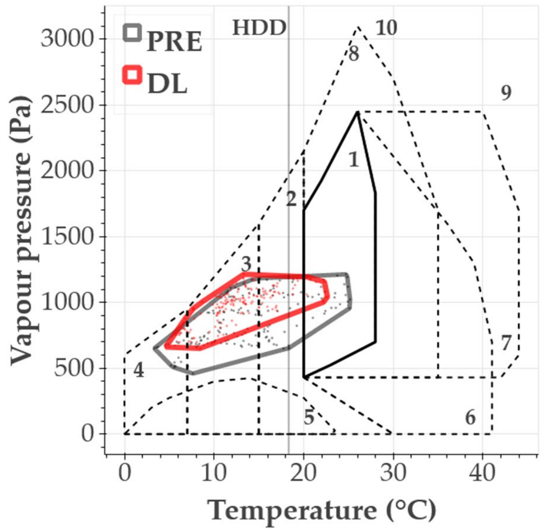
Natural gas: Heating / DHW

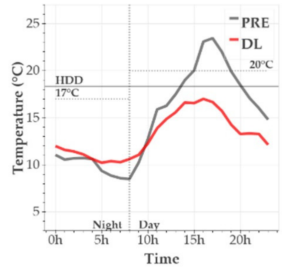
N/D

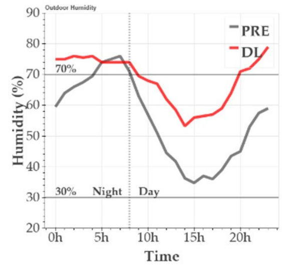
N/D

CS12

WEATHER DATA

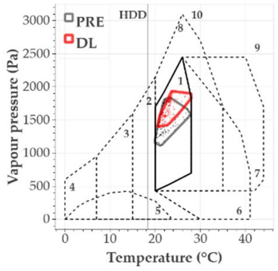


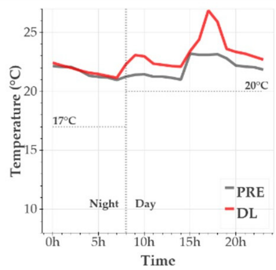


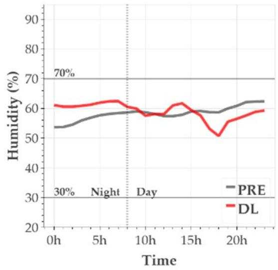


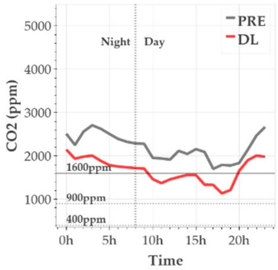
IEQ

Living room

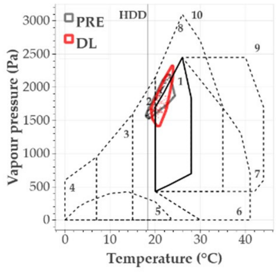


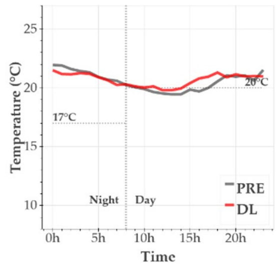


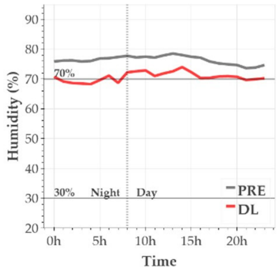


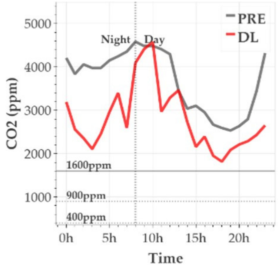


Bedroom



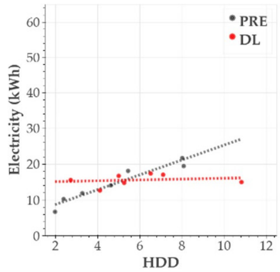


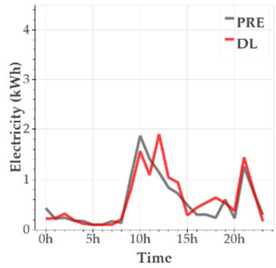




CONSUMPTION

Electricity: HVAC / Kitchen / Other





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