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New integrative tool for assessing vulnerable urban areas. Refurbishment model for energy self-sufficient and bio-healthy neighbourhoods. Madrid, Spain. HABITA-RES

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The research conducted under HABITA-RES explored the advisability of the integrative refurbishment of urban neighbourhoods on the outskirts of Madrid built between the end of the Civil War in 1939 and the enactment of the country's first building code on the indoor environment in 1979. Characterised by highly inefficient buildings, many such neighbourhoods are listed as vulnerable urban areas. The study described hereunder analysed the feasibility of their conversion to energy self-sufficiency to improve residents' environment, social circumstances and health. European directives and domestic legislation on energy production are introducing increasingly demanding requirements geared to achieving nearly zero energy buildings in 2020 and cities' carbon neutrality by target year 2050. Possible approaches to achieve those ends were assessed under this study. The theoretical model used was validated with detailed information collected *in situ* on both social circumstances and energy efficiency. Designed to study improvement strategies for both individual and groups of buildings, the model prioritises passive improvements to lower demand. The findings will enable residents in such neighbourhoods to participate actively in improvement measures and access information on their costs and benefits.

KEYWORDS

energy efficiency, vulnerable neighbourhoods, fuel poverty, urban refurbishment, urban data

1 Introduction

Integrative refurbishment of housing in vulnerable urban districts, a necessary endeavour, has been put off in Spain for a number of circumstances, most notably the housing bubble that drove new building from 2000 to 2007 and its subsequent deflation.

The tool introduced here was developed under the aegis of the HABITA-RES project (Figure 1) (Oteiza, 2018). The respective research (https://proyectohabitares.ietcc.csic.es)

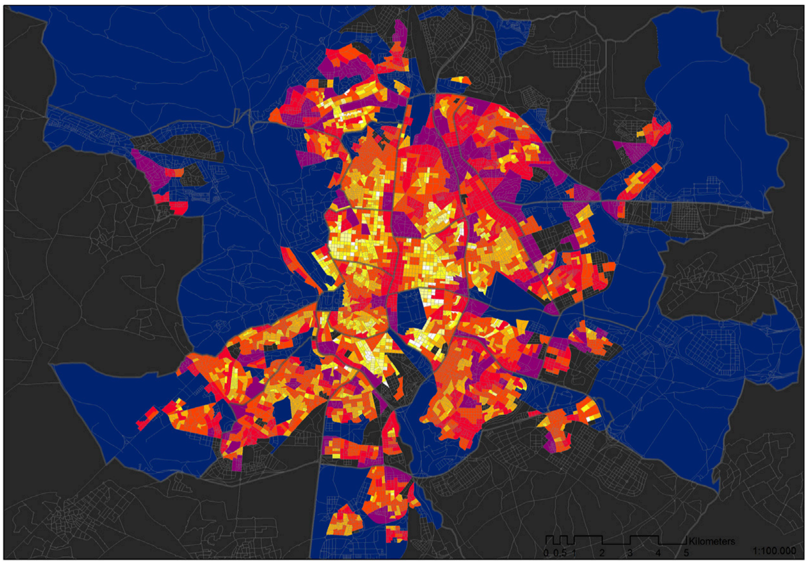

FIGURE 1
From the project website, depiction of energy intensity in the city of Madrid (Oteiza, 2018) (https://proyectohabitares.ietcc.csic.es/).

was conducted by the Eduardo Torroja for Construction Science's Institute, in the Construction System and Building Habitability research team (SCHE-IETcc-CSIC). Its closest forerunners are to be found in project REFAVIV' (Oteiza et al., 2016) (https://proyectorefaviv.ietcc.csic.es), That project addressed opaque façade behaviour in social housing in Madrid and Seville, characterising the thermal behaviour of six social housing units based on *in-situ* data HABITA-RES also builds on project Reven' (Arranz, 2015) (https://proyectoreven.ietcc.csic.es), in which the underlying assumption was that 'energy consumption associated with windows can be lowered substantially with innovative CE marking products, which also enhance indoor environmental conditions'. Its primary objective was to propose windows types best suited to social housing in refurbishment operations geared to technical and socioeconomic improvements.

Housing construction research in recent decades has revealed a need to rethink former models, now recognised as inappropriate (Cuchí and Sweatman, 2011; Cuchí et al., 2012; Cuchí and Sweatman, 2014; Casanovas et al., 2018). Further to the country's residential stock census, in Spain over five million dwellings or close to 20% of the total are more than 50 years old (INE, 2011). Around nine million Spanish residents are deemed to be affected by housing-related environmental issues with likely adverse consequences for their health (Novoa et al., 2014). A series of studies has consequently been conducted to correct urban social imbalance by defining degrees of vulnerability, differences in life expectancy and the distribution of economic resources (Howden-Chapman et al., 2007; Simcock et al., 2021). That notwithstanding, methodologies are lacking that factor in matters directly relating to the quality of housing construction that would lead, in practice, to introducing the notion 'integrative refurbishment'.

Even though housing quality and occupant health have been shown to be inter-related (WHO/CED/PHE/18.10 © Organización Mundial de la Salud, 2018; Sáenz de Tejada et al., 2021), no health plans are presently in place for urban housing. The health of the people affected by energetically inefficient buildings and so-called 'fuel poverty' are consequently in need of characterisation (Healy, 2004; Fabbri, 2015; Aranda et al., 2017). Emergencies and other disruptive and extreme developments such as the COVID pandemic (Howarth et al., 2020), in turn, have prompted the public at large to comply to one extent or another with lockdowns (Dénes and Gumel, 2019; Amerio et al., 2020) as a public health measure to curb possible SARS-CoV-2 infection (Webster et al., 2020; Jaimes Torres et al., 2021). such measures highlighted the importance of thermal comfort (Cuerdo-Vilches et al., 2021b) and in general indoor environment quality.

Europe is facing the challenge of refurbishing its existing cities to turn their potential to good account and reverse urban fabric deterioration and obsolescence. Any number of national and Europe-wide research projects have been conducted around building refurbishment (Cyx et al., 2011; Loga et al., 2016; TABULA, 2016; Bertoldi et al., 2020).

Five European directives define the pathway to energy savings and efficiency, greenhouse gas abatement, environmental protection and the prevention of climate change in general (European Parliament and EU Council, 2018; 2012; 2010; 2009; 2003). The directives at issue include 2002: on the energy performance of buildings; 2009 on the use of energy from renewable sources; 2010 on net-zero buildings; 2012 on energy efficiency; and 2018 on the energy efficiency. Essential to this discussion are the whereas clauses in 2010 Directive (European Parliament and UE Council, 2010).

At this writing household heating accounts for half of all residential energy consumption in Spain (IDAE, 2011a). A third factor that must be addressed is that in the EU from 50 to 125 million people are subject to thermal discomfort, which is detrimental to their health while contributing to social exclusion (BPIE, n.d.). It may not be wrong to assume that a considerable share of the population living in Spanish neighbourhoods built between 1939 and 1979 are exposed to 'fuel poverty'. According to reports on the subject (Tirado et al., 2012; 2014; 2018), fuel poverty affected 10% of Spanish households in 2012, 17% in 2014% and 21% in 2018. At this time 11% of Spanish households say they cannot afford to keep their homes sufficiently warm in the winter months. Many face the opposite problem in the summer (Thomson et al., 2019), which will be intensified by the expected climate change-driven rise in temperatures (IPCC, 2022).

Refurbishment may induce significant improvements in quality of life if measures are taken in buildings and the urban environment that favour societal wellbeing, social inclusion of disadvantaged communities and environmental protection. At the same time such action indisputably raises the value of the housing and building stock and would usher in a host of benefits in other areas of the Spanish economy (Dalle et al., 2010).

The work presents the development of a model that aims to study the shortcomings of buildings in terms of energy performance and the economic and social vulnerability of the population, geolocalising the problem on an urban scale. Society and the agents involved in the construction of social policies must be aware of the limitations in terms of indoor air quality and consumption in buildings. That knowledge empowers society and governments to establish policies to improve habitability conditions and the population's health by enhancing indoor environmental quality and lowering vulnerable neighbourhoods'. The paper aims to establish a specific procedure that is easily replicable through the use of public data. Any technician can easily consult these data and apply the methodology developed to make specific decisions about the study stock.

2 Project objectives

The ultimate objective pursued by the project is to improve habitability conditions and consequently the population's health by enhancing indoor environmental quality and lowering vulnerable neighbourhoods' energy dependency through an integrative approach to urban regeneration. This objective is achieved through the generation of a model, which is built with detailed information of the building an urban space.

The most prominent specific objectives of the present compilation and review of project procedures include the following.

- Identification and classification of energy-vulnerable areas by obtaining an energy vulnerability indicator associated with building that flags the needs for improvement and takes the morphology of the urban fabric into account.
- Sensitive area selection, specifying the neighbourhoods to be studied in detail and case studies to be conducted to validate the model.
- Development of a spatial analysis model based on Urban Data Science (UDS) for the integrative management of complex data by assessing the conditions in place and proposals for improving energy efficiency in buildings and their occupants' health.
- Fitting the model to and validating it with real data collected in inefficient, vulnerable neighbourhoods, applying the quantitative (monitoring real dwellings) and qualitative (surveys and other participatory techniques) results recorded.
- Assessment of the present situation by quantifying the effect of the population's socio-economic status on energy consumption.
- Assessment of possible post-reform circumstances by analysing measures to lower buildings' energy demand and adoption of renewable energies.
- Definition of indicators to support decision-making.

3 Methodology

The project focuses primarily on the development of an energy analysis model and tool. An initial assessment of energy-crucial factors that impact vulnerable urban areas served as the grounds for analysing corrective measures and integrative improvement.

Applied to a series of neighbourhoods in the city of Madrid, the model yielded a tool for visualising the most prominent energy indicators. The process was organised around three main inter-related stages, as depicted in Figure 2.

This text shows the process of generating the model through the inputs of stages 1 and 2, which will allow performing the multi-criteria analysis based on the energy and socioeconomic indicators used.

Table 1 shows the main collected data for each project stage.

3.1 Stage 1—Sensitive area selection

The first stage involved classifying and selecting sensitive urban areas with a large share of housing in need of priority energy refurbishment. The conditions presently in place in those areas were identified and diagnosed using indicators on the population's socio-economic status and buildings' energy efficiency. Those indicators include:

- Deprived neighbourhoods: which covers three dimensions of deprivation: two social (low schooling and high unemployment rates) and a third related to dwelling quality (building deficiencies),
- Inefficient buildings: calculated from the energy simulation of archetypal buildings
- Socio-economic indicators: includes indicators on low income, high energy expediture, no heating, and high proportion of population over-65 s

Procedures were developed to assess fuel poverty on the urban scale, taking Madrid as a city case study.

Existing city-scale geo-referenced spatial information found in open-access databases was analysed to identify the urban areas to be used as case studies. Building, energy and population data were drawn primarily from the National Statistics Institute's population and housing censuses (INE, 2001; 2011b). Information was also processed on vulnerable neighbourhoods (from the catalogue published by the Ministry of Public Works, Hernández Aja et al.,

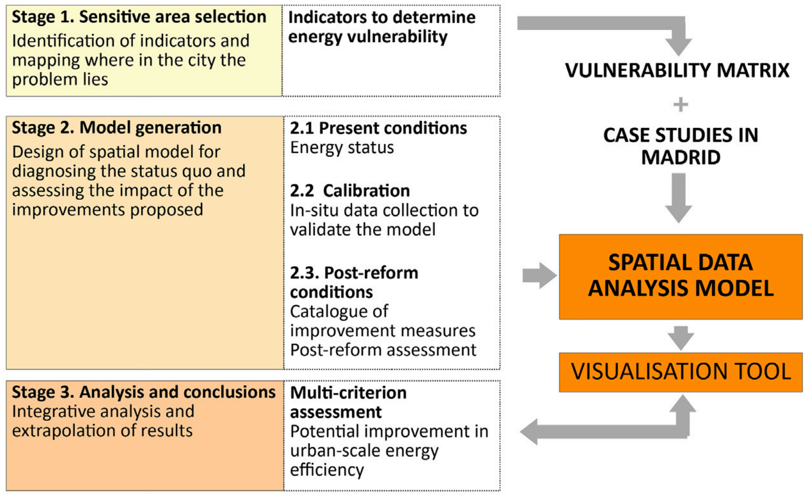

FIGURE 2
Project flowchart.

TABLE 1 Collected data.

Stage 1	City-scale geo-referenced spatial information	Building, energy and population data (INE, 2001; 2011b)
		Vulnerable neighbourhoods (Hernández Aja et al., 2018)
		Household incomes (European Environment Agency, 2017; Ayuntamiento de Madrid, 2018)
Stage 2	Spatial data	Cadastre (Sede Electrónica de Catastro, 2011)
		LIDAR point and ortho-photo data (IGN)
	Weather data	Detailed data provided by the State Agency of Theory for the city of Madrid
	Geometric and constructional information	Cadastre (Sede Electrónica de Catastro, 2011) thermal characteristics of buildings (Oteiza et al., 2018
		Optical properties in urban materials (Perez Alvarez Quiñones et al., 2021)
	Dwelling case study monitoring	Surveys
		Smart meters
		Indoor environment quality (temperature, RH, and CO2)
		Energy consumption (electricity and gas)

2018), household incomes (European Environment Agency, 2017; Ayuntamiento de Madrid, 2018) and similar.

3.2 Stage 2—Model generation

The second stage consisted in designing a spatial model for diagnosing the *status quo* and assessing the impact of proposed improvements. The model, applied on the neighbourhood scale, was fed information gathered by two procedures.

3.2.1 Theoretical model based on energy demand

In the first, top-down procedure, spatial data were analysed with a model designed to integrate information on buildings drawn from the cadastre (Sede Electrónica de Catastro, 2011) and other geographic databases.

Geometric and constructional information for the neighbourhoods analysed was compiled to estimate heating-driven energy demand, Spanish weather agency data were applied and other inputs were estimated from statistics published by national and regional institutions (INE, 2011; Instituto de Estadística de la Comunidad de Madrid, 2016; IDAE, 2019).

The model was used to study strategies for individual as well as groups of buildings and analyse neighbourhood-scale measures. The simplified procedure consists of estimating energy needs from the compensation of the energy balance. The steps of the standard ISO 13790, 2008 have been followed. It has been considered that the energy demand for thermal conditioning in the winter season is given, in a simplified way, by Eq. 1.

$$\text{Energy demand for heating (kWh)DCAL} = QG + Qi - QT - QV \quad (1)$$

Where QG = Passive solar gains, Qi = Gains from internal loads, Qt = Heat losses by transmission and Qv = Heat losses by ventilation.

A detailed description of the simplified, standard-compliant (ISO 13790, 2008) demand calculation method as applied here can be found in (Martín-Consuegra et al., 2022).

Computer algorithms and open-source software were deployed to automatically process the large quantities of data collected and determine the energy efficiency of whole neighbourhoods. A series of available web data have been used that generate content layers such as cadastral data, construction data, types of plots, etc. To integrate the different layers, download the data and process it automatically, the Python language and its Panda and Geopandas modules have been used. The vectorial and alphanumerical cadastral data downloaded were processed with Spatial Data Analysis Model (MADE) software to characterise the neighbourhood geometrically. Model output, a data sheet for each cadastral reference, showed the built volumes on each plot. In the MEPEC method, the geometric variables affecting buildings' energy performance were also included in the model. The details are described in (Martín-Consuegra et al., 2018).

3.2.2 Detailed dwelling case study monitoring

The second, bottom-up procedure entailed entering real energy performance data collected *in situ* on the individual dwelling scale into the tool. A monitoring campaign was designed and conducted on a sample of the buildings identified in stage 1. The information collected was applied to calibrate the model with data on indoor environment quality and energy consumption recorded over at least a full year.

The procedures used were based on the monitoring methods proposed for the energy refurbishment of social housing (C. Alonso et al., 2017). Surveys were conducted to determine user energy habits and analyse the consumption data recorded with smart meters as described in (Martín-Consuegra et al., 2019a).

Data collection was supplemented with a visualisation tool that integrated all the results, to which the occupants whose homes were monitored were given access from their smart mobiles, tablets and similar.

3.3 Analysis and conclusions

An integrative analysis based on multi-criterion assessment was conducted. The potential for reducing the present energy vulnerability was analysed, drawing conclusions relevant to energy refurbishment policy planning further to environmental and socio-economic criteria.

The empirical findings were compared to the consumption values estimated from the heating energy demand found with the theoretical model. The lag between theoretical and monitored consumption was analysed to define the most suitable focus for urban refurbishment operations (de Frutos, F. et al., 2020).

The impact of envelope improvement measures based on theoretical estimates and refurbished and non-refurbished building monitoring was also assessed (Martín-Consuegra et al., 2021).

Table 2 sumarizes the main field studies conducted previously for each stage:

4 Results

This section includes the most significant results from the Madrid case study. The findings discussed in this section spawned advances in a number of the dimensions addressed in the study. Some have also been published in specific congress papers or earlier articles in scientific journals (table 2).

4.1 Sensitive area selection and representative buildings (stage 1)

The order of magnitude of energy demand needed to reach indoor comfort levels in all the housing registered in the city of Madrid in 2011 was estimated for a standard winter. The criterion used was the definition of comfort conditions set out in the national technical building code (CTE-DB-HE, 2013), the building thermal characteristics analysed by construction year, and the climate of the city of Madrid. Further to that estimate, in 2001 around 10 750 000 MWh (924 333 ktoe) of thermal energy were needed yearly to heat Madrid's housing stock (Martín-Consuegra, F. et al., 2016).

4.1.1 Energy poverty in Madrid

The first stage of the study focused on locating the most disadvantaged areas of the city in terms of building-related energy vulnerability (Alonso et al., 2013; Martín-Consuegra, 2014). Whole pockets of inefficient, high energy cost buildings were identified.

One of the findings showed that various causes of energy poverty (high cost, low income and energy inefficiency) are often jointly present. An analysis of energy costs and household incomes detected low income areas where many of the buildings are inefficient, for families with fewer resources often live in (now obsolete) areas developed prior to 1979. The absence of suitable heating facilities in many homes in those areas translates into higher occupant costs to meet basic energy needs. The result is a vicious circle that affects the most impoverished segments of the population, intensifying their vulnerability (Martín-Consuegra et al., 2019b). Some households in the lowest income brackets were observed to be at risk of fuel poverty regardless of the energy efficiency of their dwelling, however. The inference is that specific public policies tackling fuel poverty must be instituted to supplement energy refurbishment plans. Reciprocally, operations that improve building energy efficiency would lower the number of cases and the sums required to fund such policies (Martín-Consuegra Ávila, 2019).

A multi-dimensional indicator of energy poverty was developed that can catalogue urban areas by their level of risk (Martín-Consuegra et al., 2020). A review of these priority areas for public energy intervention policy determined the case studies chosen for monitoring and detailed analysis.

TABLE 2 Main field studies conducted for this project.

Stage 1. Sensitive area selection	
	• Energy needs and vulnerability estimation at an urban scale for residential neighbourhoods heating in Madrid (Spain)
	• Distribución de la pobreza energética en la ciudad de Madrid (España)
	• Multidimensional index of fuel poverty in deprived neighbourhoods. Case study of Madrid
Stage 2. Model generation	
	Theoretical model based on energy demand
	• Use of cadastral data to assess urban scale building energy loss. Application to a deprived quarter in Madrid
	• Utilización de datos catastrales para la planificación de la rehabilitación energética a escala urbana: aplicación a un barrio ineficiente y vulnerable de Madrid
	• La envolvente energética de la vivienda social. El caso de Madrid en el periodo 1939-1979
	• Classification of roof types in existing residential buildings in madrid. Data for an energy rehabilitation strategy
	Detailed dwelling case study monitoring
	• Methodological proposal for monitoring energy refurbishment. Indoor environmental quality in two case studies of social housing in Madrid, Spain
	• Energy consumption and comfort gap in social housing in Madrid, through smart meters and surveys information
Results	
	• Energy efficiency and comfort on a deprived neighbourhood in Madrid (Spain) The gap between a predictive model and measured data on energy consumption, addressing indoor environmental quality assessment
	• Minimal Monitoring of Improvements in Energy Performance after Envelope Renovation in Subsidized Single Family Housing in Madrid
	• Experimental Analysis Of The Optical Response Of Opaque Surface Finishes In Cities. The Case Of Madrid
	• Applicability of a passive radiant-capacitive heating and cooling system in the rehabilitation of residential buildings. Case study: Colonia de San Carlos, Madrid (Spain)
	• Analysis of Building Archetypes for Optimising New Photovoltaic Energy Facilities: A Case Study
	• Indoor Environmental Quality and Consumption Patterns before and during the COVID-19 Lockdown in Twelve Social Dwellings in Madrid, Spain

4.1.2 Selection of representative buildings to be monitored

Identifying buildings in the areas of interest proved to be a particularly complex task. Support was received from the city's Municipal Housing and Land Company, its Sustainable Development Division through the MAD-RE (Madrid-Recovery, 2018) Plan, the Guetaria neighbourhood community association and the Technical University of Madrid's School of Architecture.

The buildings selected for monitoring are located in complexes on the outskirts of the city developed between 1940 and 1980. Widespread inefficiency in these neighbourhoods necessitates energy refurbishment. Three of the buildings are located in priority refurbishment areas, catalogued as vulnerable, and the other three in areas adjacent to vulnerable neighbourhoods (Figure 3).

4.2 Model for analysing spatial data (stage 2)

4.2.1 Spatial energy demand model

A spatial data model was built with geometric and constructional data compiled from different sources. Heating energy demand for whole neighbourhoods was then calculated using the model's simplified approach.

Energy consumption was computed for all the residential buildings in the six neighbourhoods studied, assuming demand was fully covered (theoretical consumption). Figure 4 illustrates the heating demand calculated for the whole neighbourhood.

Once developed, the model constituted a tool able to determine energy loss from cadastral data. Denominated the Energy Loss Assessment Method (MEPEC), its details are described in (Martín-Consuegra et al., 2018). It was used to simulate the post-improvement decline in energy demand.

- Geometric information

The energy loss assessment tool automated the collection of geometric data contained in the cadastre.

- Constructional information

Energy demand calculation entails characterising the thermal envelopes that separate the indoor from the outdoor environment, such as façades (including their blank walls and openings), roofs and floors. In Madrid, the aforementioned REFAVIV project collected data from the original designs for a sample of 75 housing developments built prior to 1979 (Oteiza et al., 2016). That information was compiled in a monograph on the thermal characteristics of these buildings (Oteiza et al., 2018). and entered into the present spatial data model to define construction categories.

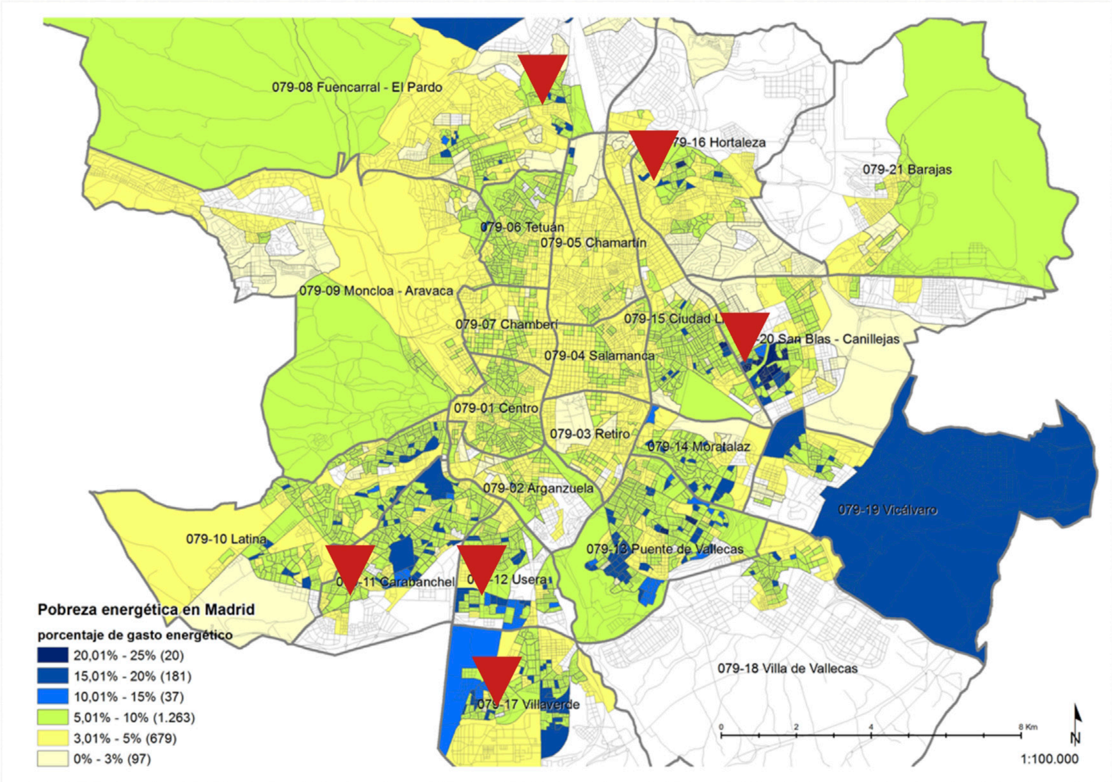

FIGURE 3
Distribution of energy poverty in Madrid found with the cost by income method (Martín-Consuegra et al., 2019b) and location of the sample monitored.

FIGURE 4
Yearly heating demand in two of the developments analysed in the study.

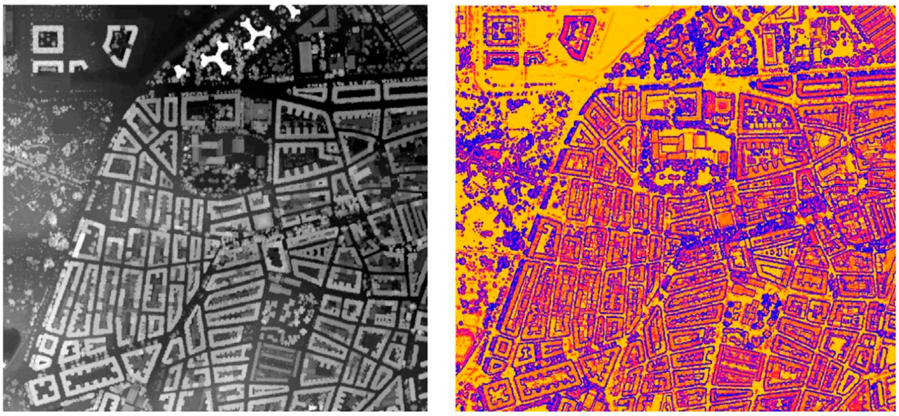

FIGURE 5
Data sources for the area analysed: **(A)** digital elevation model for the area analysed; **(B)** model-defined pitch.

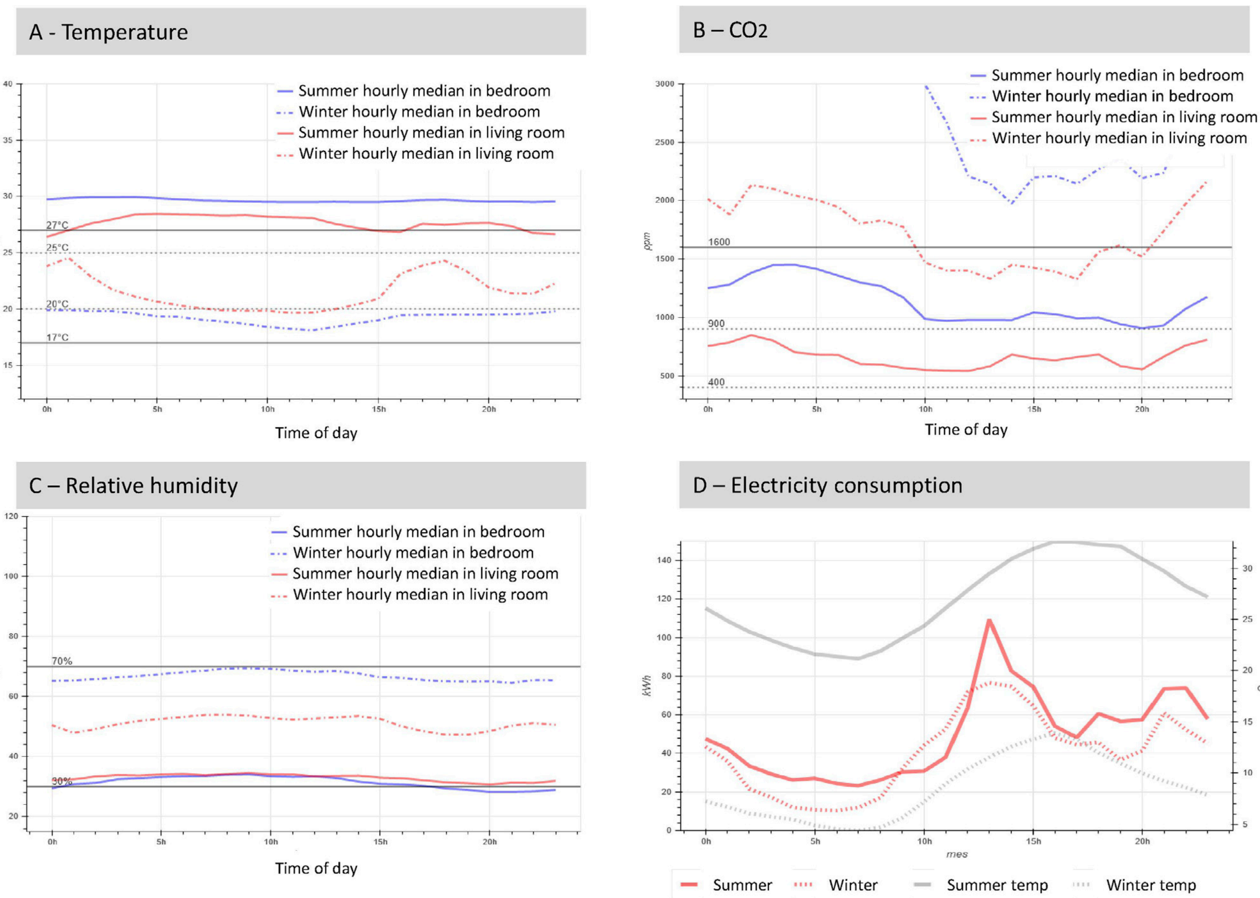

FIGURE 6
Data for two rooms in one of the dwellings monitored: **(A)** temperature, **(B)** CO_2 **(C)** relative humidity, and **(D)** energy consumption.

Amethod to characterise roofs based on open access geographic information was developed to factor that component into the analysis, drawing from LIDAR point, cadastral and aerial ortho-photo data (Alonso, C. et al., 2019). Figure 5 shows two images of the geographic information process.

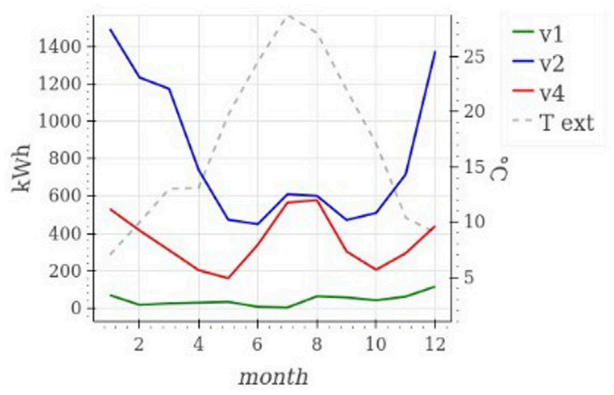

FIGURE 7
Energy consumption curves for three homes in Madrid (raw data from smart meter readings)(Martín-Consuegra et al., 2019a).

4.2.2 Surveys

Two surveys were conducted, one at the outset and the other after the units had been monitored for over a year on average, in the midst of the COVID pandemic. That circumstance afforded the opportunity to collect data on energy consumption and indoor environmental quality in Madrid housing during lockdown. The combination of objective (consumption and environmental parameter monitoring) and subjective (behavioural patterns and user perception during lockdown) data yielded information on the effect of compulsory 24/7 occupancy on indoor environmental quality and consumption patterns in 12 housing units.

4.2.3 Monitoring

Once the areas of interest were defined, several dwellings located in pilot buildings in the neighbourhoods were monitored to acquire detailed information on habitability and energy consumption. A total of 26 homes in 6 neighborhoods in Madrid were monitored.

Data collection was undertaken stepwise in 2019–2021 with the intention of gathering data for a full year on temperature, relative humidity and indoor air quality (CO2) in two rooms, along with outdoor parameters from rooftop meteo stations on the respective buildings (Figures 6, 7). Figure 6 shows, as an example, the type of data collected in one of the dwellings, differentiating the information from the living room and bedroom in both winter and summer. As the average temperature is observed throughout all hours of the day, they are outside the comfort range in summer and much of it in winter. the energy consumption curves of the 3 different cases for three homes shows the differences between three dwellings in the same building, where the user and the use of the environmental conditioning systems are very different (Figure 7).

Occupants were shown the findings, to enable them to compare their energy consumption levels and indoor environment with the recommended comfort parameters in the Givoni bioclimatic chart (Figure 8). This graph shows the monitored temperature and humidity data and helps the occupants to choose the most appropriate bioclimatic strategy (from 2 to 10) to approach the comfort zone initially marked in the green zone (zone 1).

The experience with monitoring has led to other developments such as those being carried out on HabitMadrid strategy, with the construction of a platform that collects scientific data on the efficiency improvement of the renovation of residential buildings (Martín-Consuegra et al., 2021) (https://habitamadrid.ietcc.csic.es/).

4.2.4 Local measurement of surface optical properties in urban materials

Further to the model's definition of urban outdoor spaces as a refurbishment target, the optical properties in the solar radiation range of a number of surface finishes bounding those spaces were measured. The experimental solar absorptance of such finish materials was obtained to assess their impact on both building energy performance and the urban microclimate (Perez Alvarez Quiñones et al., 2021).

4.2.5 Differences between estimated and empirical data-model calibration

One of the key aims of the study was to determine the energy profiles of housing units in vulnerable areas and the gap between those profiles and the standards used in energy analyses. A comparison of the two datasets revealed differences.

Cross-referencing invoices issued on the grounds of smart meter readings with the energy profiles deduced from user surveys showed some households' consumption to be insufficient to meet basic needs (Martín-Consuegra et al., 2019a).

When model-estimated consumption assuming demands were met was compared to the consumption monitored (de Frutos, F. et al., 2020), significant differences were observed in social housing in the Villaverde Bajo neighbourhood (Figure 9). The relationship between the resulting consumption divide and indoor environmental quality, in turn, identified households experiencing fuel poverty and defined the social circumstances to be borne in mind in energy refurbishment strategies.

4.2.6 Use of renewable energy

With energy demand defined, an analysis was in order of the effect of including renewable sources in the mix to determine the feasibility of self-sufficiency in the neighbourhoods concerned.

The potential of a night time radiative cooling and the applicability of a radiant-capacity cooling system for passive or low-energy environmental control were analysed for one of the case studies in the Villaverde neighbourhood. The findings showed substantial potential for lowering final air conditioning energy demand in the summer months. Predictive formulas and Energy Plus thermal simulation software were used to simulate application of the system developed and experimentally assessed at Universidade Teconologica Federal do Paraná, UTFPR, Curitiba, Brazil by E. González and E. Krüger to a dwelling in Madrid's Villaverde neighbourhood (Figure 10). Significant cooling potential was found for the building studied, whose thermal performance was further improved by the thermal mass of its envelope and system radiant-capacitive modularity. During the summer the indoor maximum and minimum temperatures remained within the adaptive comfort range most of the time with no superheating (González-Cruz et al., 2020).

Another study was performed for analysing the integration of PV panels in these buildings (Fernández-Agüera et al., 2021). The case study at issue analysed the situation prevailing in Canillas, one of Madrid's listed vulnerable neighbourhoods. The Sun's path, irradiance and shading were analysed to identify the rooftop

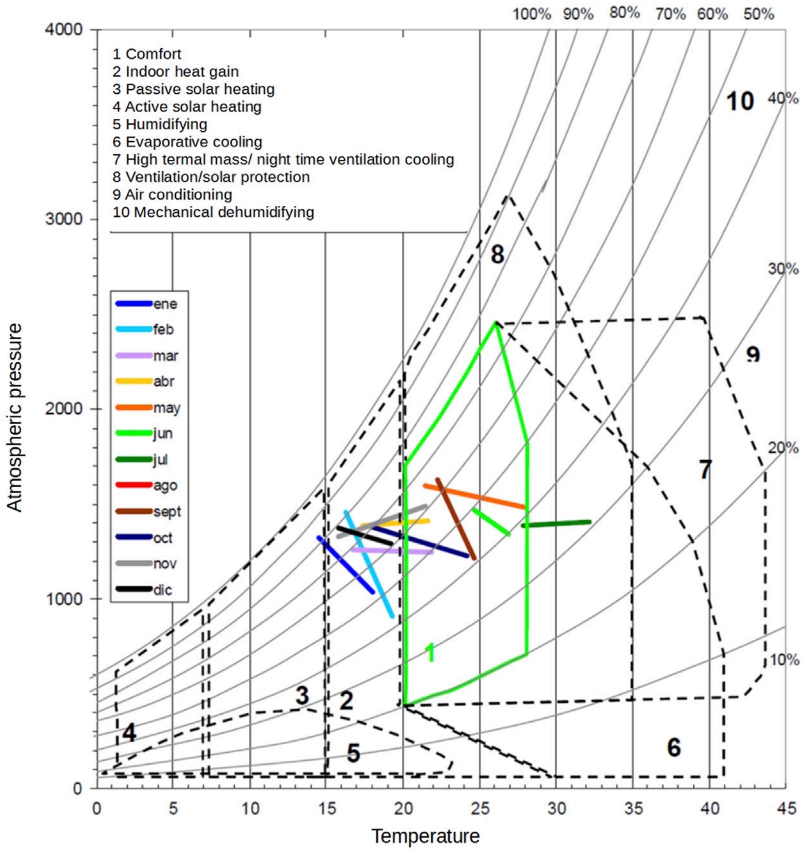

FIGURE 8
Psychometric chart for one of the dwellings monitored (01-02-2019 to 31-01-2020: the green lines bound the comfort zone and the numbered areas lying outside it the zones for the strategies listed in the box).

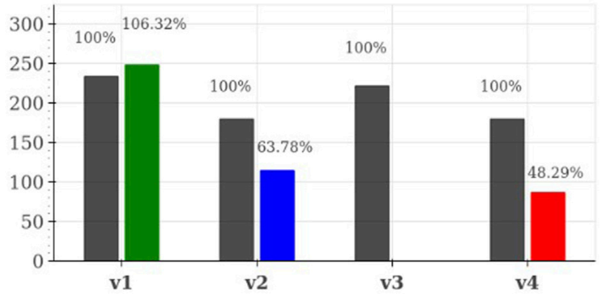

FIGURE 9
Real consumption/assumed demand divide in four dwellings (de Frutos, F. et al., 2020).

areas best suited to housing PV panels (Figure 11). That second study explored and provided a detailed account of the solar potential of residential building archetypes found in peripheral and outlying neighbourhoods in Madrid.

To obtain a profitable use of the possibility of photovoltaic production, a sunlight study is carried out for the building complex. This study is carried out for each month of a typical year with the idea of obtaining possible conflicting locations due to shadows on the roof, which can alter the results of the study. This first analysis allows us to identify the areas with the greatest potential and the most problematic areas.

This study is done using a pluggin of the Sketchup modeling tool called ShadowAnalysis. It provides data of hours of shade in a range of 0 to +10 h and a study is carried out for 1 day of each month. The program studies the incidence of sunshine between 7 am and 21 pm (14 h). After this process you can check the possibility of the existence of shadows thrown from one building to another, necessary to take into account in the installation of photovoltaic panels, in addition to the shadows themselves belonging to the irregularities of the roof of each building. It is necessary to identify towers, ventilation chimneys, parapets, or other elements.

For the calculation of photovoltaic production, the hourly energy balance method is used. This analytical method allows to size the photovoltaic system according to the conditions of energy consumption and meteorological data of the location of the case study. The main purpose is to seek an adjustment of photovoltaic generation to the demand conditions of a certain environment in a specific period of time. The capacity of an hourly energy balance is the opportunity to evaluate an energy system based on a load and established meteorological data, to achieve an optimal design of the future installation.

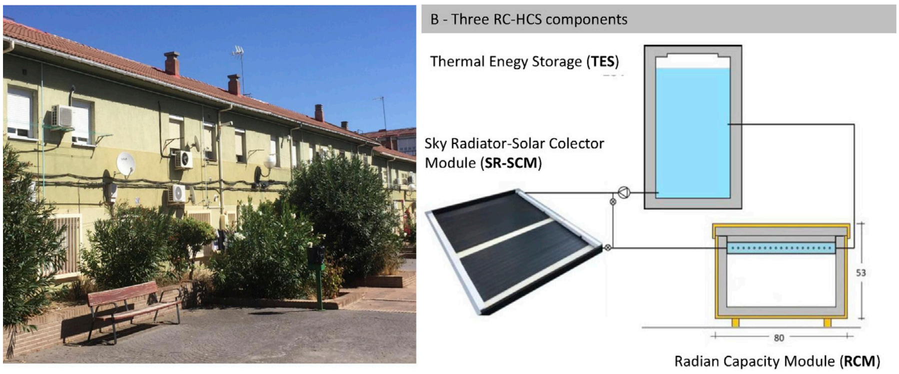

FIGURE 10
Colonia de San Carlos' housing complex, Villaverde, Madrid; **(B)** three RC-HCS components: radiant-capacity module (RCM), sky radiator(solar collector (SR/SC) and thermal energy storge (González-Cruz et al., 2020).

FIGURE 11
Year-round monthly shading patterns in Canillas, Madrid.

The estimation of photovoltaic production is carried out using the PVGIS software. It is necessary to take into account and foresee the characteristics of each installation including modules (type and number), inclination, orientation, etc. In addition to the irradiation and temperature data provided by the State Agency of Theory for the city of Madrid. This tool is developed by the European Commission's Science. The results of the neighborhood and its energy potential that this tool contributes to the study are the following: monthly percentage of losses; general losses of the installation; average annual, monthly and daily electricity production; average annual, monthly and daily solar radiation.

4.2.7 HABITA-RES and COVID-19

The COVID-19 pandemic, which is ongoing although with waning severity, broke out in spring 2020 when the project was fully underway. More specifically, in March 2020 Spain's national government decreed a state of emergency mandating a strict lockdown that remained in effect until 21 June (Agencia Estatal Boletín Oficial del Estado, 2020).

The sub-project undertaken on the occasion entitled COVID-HABITA-Res, reviewed survey responses and recorded data in its comparison of data sources to triangulate the main study on the grounds of: 1) variation in consumption, comfort and indoor air quality patterns before/during the COVID-19 pandemic; and 2) a deeper analysis of the nuances among objective data, the values assumed by academia as 'satisfactory or adequate' and users' subjective perception of environmental parameters, hygrothermal comfort and energy consumption. The joint analysis had a dual purpose, as premised in methodological triangulation, namely:

1) to broaden the scope of the research by drawing from different data sources.
2) to enhance research quality control and therefore the reliability of the findings (Olabuénaga, 2012). In this case the reliability of the results also provided insight into households' subjective perception of the parameters monitored, namely comfort, air quality and power consumption.

The findings showed that the building characteristics initially in place and household predisposition had a conclusive effect on the variation in consumption and indoor environment quality patterns. Initial conditions varied widely and were also impacted by household composition and practice, along with everyday routines and habits and consequently energy behaviour. The findings of that analysis are discussed in greater detail elsewhere (de Frutos et al., 2021).

5 Conclusion

The most prominent outcome of HABITA-RES is a complex and dynamic model that draws from detailed information collected *in situ*. The model can be used to perform different types of analysis to determine the advisability of integrative refurbishment in neighbourhoods on the outskirts of large cities. Refurbishment in vulnerable neighbourhoods is broached from several perspectives with the data delivered by the model.

Overall, the study addressed the possibility of improving both individual buildings and whole complexes, particularly *via* passive improvements to lower demand and establish self-sufficient neighbourhoods with a view to enhancing the populations' environment, social conditions and health.

The focus was on vulnerable areas and identifying those in need of urgent public action to improve neighbourhood-wide energy efficiency. The resulting reference materials included accurate studies of fuel poverty conducted in the city of Madrid.

In all, 26 housing units were monitored to collect detailed *in-situ* data to explore habitability and energy usage, establish consumption profiles and identify differences between assumed and empirical consumption. The analysis of present energy consumption and habitability conditions constitutes the baseline for designing real data-based energy refurbishment policies for this residential stock.

Under the circumstances created by COVID-19, dwellings were inevitably occupied more assiduously to comply with national government mandates. The resulting changes in habits and occupancy patterns entailed higher energy consumption and variations, not necessarily adverse, in air quality and hygrothermal comfort demand over longer than usual periods. In addition to household core composition and practice, building design and upkeep had a significant effect on the response to lockdown. Energy savings strategies prompted by higher consumption were more intense in households where the initial physical and environmental conditions were less favourable. The primary takeaway to be drawn from the study is how such unusual and extreme situations affected the least energy-efficient dwellings and their occupants. The study conducted may serve as a guide for other scenarios such as extreme weather conditions including heat and cold waves and those envisaged by the IPCC for 2050, and particularly their effect on vulnerable segments of the population such as the elderly and the chronically ill, who may be home-bound for periods similar to those analysed.

None of the dwellings was fitted with a renewable power generation system, a solution desirable not only now in response to demands for decarbonisation and energy transition, but especially in the lockdown-induced context of uncertainty around worldwide resources in general and housing and household facilities in particular.

The multi-dimensional analysis conducted in the neighbourhoods sampled is illustrated by the visualisation tool found on the project website (https://proyectohabitares.ietcc.csic.es/) (Oteiza, 2018).Alonso et al., 2017 CNUCC, 2015 Cuerdo-Vilches et al., 2021a Cuerdo-Vilches and Navas-Martín, 2021 Flores et al., 2018 Martín-Consuegra et al., 2015 Ministerio para la Transición Ecológica y el Reto Demográfico, 2020 Navas-Martín et al., 2021 European Parliament and UE Council, 2010a, Oteiza et al., 2016.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: https://proyectohabitares.ietcc.csic.es/.

Author contributions

Habitares project was directed by IO,and has been developed collaboratively by all the authors, each one in its area of expertise.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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