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Disconnected, yet in the spotlight: Emergency research on extreme energy poverty in the Cañada Real informal settlement, Spain

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ABSTRACT

Cañada Real is a 15-km informal settlement located in Madrid, Spain. With over 8000 inhabitants most dwellers live below the poverty line in informal, low-quality housing. Due to the impossibility to have legal supply contracts with utility providers, Cañada Real settlers have relied on irregular connections to nearby electricity and water distribution networks for decades. However, in October 2020, technical changes implemented by the distribution system operator left some 4000 people without access to power, and more than two years later a large share of them remain in those conditions. Emergency research has been conducted to document the change in living conditions experienced by Cañada Real residents. Census data have been analysed together with primary data from a 39-household survey, data retrieved from electricity service continuity sensors and direct measurements of indoor thermal comfort in 12 households. This set of data provides unique evidence on the impact of a collective disconnection event of an unprecedented magnitude in an EU context. Results give evidence of a case of 'extreme energy poverty' that existing datasets and indicators fail to capture. The collective adaptation response displayed by a group of residents, who agreed on an intermittent, predictable disconnection schedule, highlights social fabric, self-organization and local capacities as resilience factors that provide temporary relief. Still, collective reconnection appears as a necessary first step to secure a minimum level of material living conditions. Political action is needed to modify the existing framework that marginalizes vulnerable dwellers as non-compliant customers, without any provisions against supply disconnections.

1. Introduction

Lack of access to energy - and especially to 'modern' sources of energy such as electricity or natural gas - has traditionally been a matter of policy and research concern primarily in the Global South [1,2]. As billions of people across developing world nations remain disconnected from the electricity supply and depend on traditional biomass for cooking and heating [3], research has highlighted significant gendered- and age-determined impacts of living in indoor-smoked polluted environments, lack of lighting at night for studying at home, poorer hygienic conditions or reduced income generation opportunities [4,5] that affect women and children disproportionately. In developed countries - and in Europe in particular, following the seminal contribution of Boardman in 1991 [6], the emphasis of the fuel/energy poverty literature has mostly been on the affordability of domestic energy services, primarily space heating [7]. Such a restricted understanding of the issue is in line with the assumption that practically all people in the Global North have access to high quality energy carriers, as mass electrification, and the steady expansion of natural gas distribution networks in the 20th century have fuelled modernist rhetoric about universal access to high-quality energy carriers in developed regions. However, these imaginaries clash with the reality of hundreds of thousands of energy-poor households having their supply disconnected every year due to arrears and indebtedness in affluent countries such as Germany [8] or Spain [9]. Similarly, increasing attention paid to the issue of 'hidden energy poverty' in Europe – understood as households' self-rationing of energy use at home below levels required for an adequate, dignified life [10] – speaks of household energy underconsumption as a form of energy poverty that resembles conditions experienced by people having lost access or irregularly connected to the supply. In Central and Eastern Europe, the persistence of and relapse into 'traditional' solid fuel-based modes of domestic heating by low- and middle-income households – a

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process labelled as 'energy degradation' – equally challenges the assumption of unrestricted access to electricity and natural gas in developed world contexts [11].

Informal settlements and 'slums' shelter a substantial part of the vulnerable populations both in the Global North and Global South, and present singular characteristics in relation to access-related energy poverty. Although both terms (informal settlements and 'slums') are often used indistinctly, some differences apply from a conceptual and policy perspective. On the one hand, 'urban slums' have been defined as "residential areas with substandard housing that are poorly serviced and/or overcrowded, and therefore unhealthy, unsafe, and socially undesirable" [12]. On the other hand, informal settlements are, according to UN Habitat (2003), residential areas which are either constructed on land that the occupants have no legal claim to, or not in compliance with current planning and regulations [13]. The UN Sustainable Development Goals (SDGs) framework defines indicator 11.1.1 ('Proportion of Urban Population Living in Slums') as "the proportion of the population that live in slums, informal settlements and those living in inadequate housing" [14], which adds to the picture the dimension of 'inadequate housing' as unsuitable dwellings from the point of view of security of tenure, availability of services, affordability, habitability, accessibility, location and cultural adequacy [15]. According to this SDG 11.1.1 indicator, as of 2020 informal, inadequate or slum settlements were home to one billion people worldwide (one quarter of global urban dwellers), of which 85 % lived in three regions: Central and Southern Asia (359 million), Eastern and South-Eastern Asia (306 million), and sub-Saharan Africa (230 million) [16]. Most of these are in or around urban areas where problems of inadequate, unaffordable housing concentrate and are expected to increase in parallel to global urbanization trends [17]. In Spain, World Bank data for 2018 indicate that 5.5 % of its urban population were 'slum households', i.e., "lacking one or more of the following conditions: access to improved water, access to improved sanitation, sufficient living area, housing durability, and security of tenure" [18]. However, considering the criticism that the term 'slum' has attracted for its negative connotations and imaginaries [19–21], for the purposes of this research we primarily refer to Cañada Real – our case study site – as an informal settlement.

The causes of informal settlement emergence and expansion worldwide are wide ranging: national and cross-border migration to rapidly growing urban areas where affordable housing is scarce and planning is poor; displacement of refugees fleeing from armed conflicts, natural disasters or climate-change related weather hazards to temporary shelters that then become their permanent residence; or as a coping strategy among people affected by the financial hardship (e.g., evictions) or housing shortage. Substandard housing, lack of access to basic services and overcrowding represent distinct vulnerability factors for energy poverty, while all informal settlements, regardless of their origins, share the common issue of lacking land property rights, construction permits or housing ownership [15,22]. These are central energy poverty issues, as legal access to the energy supply generally requires proof of dwelling formality, a legal restriction that leads households in informal settlements to resort to informal connections to energy (and water) distribution networks [23].

Issues of energy access in informal settlements have been explored to some extent in the Global South [24,25], in particular in uncontrolled growing metropolitan areas in emerging countries [26,27]. Recent research on the topic has highlighted the energy and food security impacts of COVID-19 pandemic on informal settlement households in Kenya, who were forced to reduce food intake and switch to lower quality fuels during lockdowns [28]. Technology such as microgrids based on solar PV on rooftops has proven an effective solution for giving access to higher tier electrification and, consequently, to address energy access issues in off-grid informal settlements [29]. However, participatory approaches sensitive to people's fuel choices are essential to develop effective solutions and to empower people, as energy access issues cannot be addressed by technology alone. In this regard, non-energy policies tackling housing and land tenure issues are crucial to secure access to modern energy services as they are a prerequisite for informal settlements to connect to the natural gas network, and to a safe electricity service [30]. In the Global North, European energy poverty scholarship so far has seldom engaged with irregular and insecure access to energy, with exceptions - see Babourkova [31] for a case study on irregular access to electricity in Roma settlements in Bulgaria. And, to the authors' knowledge, no prior research exists on the issue of collective electricity disconnections as an 'extreme energy poverty' [32] topic that only recently has been recognized by the energy poverty and justice literatures [33].

This research aims to fill this gap by focusing on the case of Cañada Real (Madrid, Spain). Cañada Real Galiana (or Cañada Real, in short) is one of the largest – if not the largest – informal settlements in Europe with widespread issues of lack of legal land and housing ownership, and, in some parts, of substandard and poorly serviced housing. Cañada Real provides, on the one hand, a prime example of lack of access to basic energy services as experienced in other Global North informal settlements due to informal housing conditions. On the other hand, it makes for a unique energy emergency case of unprecedented magnitude in the EU in which a population of several thousands was suddenly disconnected from the electricity supply in autumn 2020 – and remains so at the time of writing this piece. Against this background, this work aims to explore collective disconnections as an extreme case of energy poverty in informal settlements by documenting the living conditions of Cañada Real after the interruption of electricity supply in October 2020. To do so, the paper is structured as follows: Section 2 introduces Cañada Real as a case study and justifies the need for conducting emergency energy research; Section 3 presents the four datasets and the overall analytical approach employed; Section 4 features the main quantitative results of the assessment; and Section 5 provides key discussion points and main conclusions of the research.

2. Cañada Real: making the case for emergency energy poverty research

In its origins, the land now occupied by the Cañada Real Galiana settlement was an uninhabited drover's road or livestock route for transhumant cattle running in a North-South direction (from La Rioja to Ciudad Real) just next to Madrid (Spain). Since Act 3/1995, of 23 March, on Cattle Trails, Spanish legislation recognizes these roads as public domain assets whose ownership is generally attributed to Spanish regional administrations (*Comunidades Autónomas*). The first country houses informally erected in Cañada Real Galiana date back to the 1950s and 1960s. They were built by Spanish migrants arriving to the capital city from impoverished rural areas of Central and Southern Spain in search of work and better living conditions, or as secondary residences by people already established in Madrid. These early dwellers were later joined by waves of new settlers including Spanish Roma (*gitano*) people, Moroccan and Romanian (often Roma too) migrants, and families relocated after the demolition of shanty towns located in the urban peripheries of Madrid [34,35]. Unlike other such communities that have been either dismantled or integrated in the formal urban fabric of the Madrid metropolitan area, Cañada Real remains an informal settlement up to this date and, in fact, is said to be the largest informal settlement in Europe [36].

In its current form, Cañada Real is a long-standing settlement located in a 14 to 16 km-long (figures and definitions vary) and 75 m-wide linear strip some 15 km to the South-East of downtown Madrid. Starting in the municipality of Coslada, it extends in a linear direction south to Getafe, through the municipalities of Madrid and Rivas-Vaciamadrid. It is administratively constituted by 6 'sectors': Sector 1 is embedded in the urban core of Coslada, Sectors 2, 3, 4 and 5 run along the administrative boundary between the Rivas-Vaciamadrid municipality and the Vicálvaro district of Madrid, and Sector 6 – the largest and most populated section, – is located mostly in the Villa de Vallecas district of Madrid and ends in the outskirts of Getafe.

The actual population of Cañada Real Galiana has been a subject of discussion. In 2012, a first census approximated the total population to 11,000 inhabitants, and then again to some 8600 people [37]. The second and up to now latest census, conducted between 2014 and 2016, estimated a total population of some 7200 people. Since then, more than one hundred families from Sector 6 have been rehoused outside Cañada Real by social services.

Efforts to improve the living conditions of Cañada Real dwellers and find the "most favourable solution" for the 'irregular settlement' led to the signature of the Regional Agreement for Cañada Real Galiana [38], on May 17, 2017. Signatories include the national government through the Spanish Government Delegation in the Madrid region, the regional government of the Autonomous Community of Madrid, the Coslada, Madrid, and Rivas Vaciamadrid city Councils, and the political parties represented in the regional parliament of the Madrid Autonomous Community. This agreement marked a rare moment of unanimity of political representatives and concerned administrations and defined a roadmap for a definitive 'solution' for Cañada Real. The main objectives of the agreement, which remain unfulfilled at the time of writing this article, are described as follows [38]: 1) to "restore the natural environment" of the Cañada Real territory in areas unsuitable for residential or economic activities; 2) to 'regularise' the property status of Cañada Real housing and plots of land following "principles of legality, the right to housing and the right to the city"; 3) to develop a strategy for the relocation of the settlement's population that, whether for "territorial, environmental, security or health reasons" cannot continue living in their Cañada Real dwellings; and 4) to "adopt urgent measures to safeguard the integrity, health, services and integration of the most disadvantaged population" of Cañada Real in accordance with the Universal Declaration of Human Rights (1948), the World Charter for the Right to the City (2004) and the United Nations Conference on Housing and Sustainable Urban Development 'Habitat III'.

From an energy poverty perspective, Cañada Real makes an outstanding case of lack of secure and reliable access to the energy supply in a Global North context. For decades, most of the Cañada Real residents have relied on irregular connections to the electricity grid (and to the water supply network) as utility providers have been unable to offer legal supply contracts to households living in informal housing. Such relatively precarious access conditions were dramatically altered in the early days of October 2020, when the distribution system operator (DSO) implemented technical changes (reportedly based on network security concerns) in the local power distribution infrastructure to which most residents are informally connected, which ultimately resulted in 60 % of the settlement's population (those living in Sector 5 and Sector 6) losing access to electricity. Cañada Real quickly made it to the headlines of Spanish and international media with stories reporting families left in the cold and darkness and children unable to join online classes in the midst of COVID-19 lockdowns – see for instance the article "'You kind of die': life without power in the Cañada Real, Spain" published in The Guardian on October 27th, 2021 [39]. Since local and regional administrations and the DSO in the area have not provided an effective solution since October 2020, most of Cañada Real's Sector 6 residents remained without access to the supply at the time of publication of this article in summer 2023, thus experiencing more than two years of significantly precarious living conditions. In Sector 5, electricity access conditions have somewhat improved since the October 2020 shutdowns through community self-organization, which has succeeded in adjusting the aggregated electricity demand (by disconnecting parts of the sector in turns) to the new capacity requirements of the local section of the grid to which they are connected. Furthermore, in March 2022, a police intervention to dismantle a marijuana plantation in Sector 4 resulted in damages to the 'irregular' (self-installed) grid that left without power for almost a month a large part of Sector 4, the whole of Sector 3 and half of Sector 2 [40,41]. Since then, temporary outages have been taking place in these sectors as well. Such ongoing developments suggest that the conditions endured by Sector 6 residents since October 2020 risk spreading to other sections of the settlement.

The Cañada Real case presented in this research thus opens the door to expand energy poverty scholarship in the following directions. First, it addresses a significant gap in the energy poverty literature, which so far has primarily considered 'well-established' vulnerable populations (e.g., low-income, children, elderly, single-parent households, etc.) and has seldom investigated informal settlements. The research also adds to previous works that had investigated coping strategies through which vulnerable populations respond to energy poverty – in this case, to extreme poverty conditions resulting from the collective disconnection of a whole community - [42]. It then provides accurate sensor-based data and metrics on the indoor comfort of dwellers whose material living conditions have been dramatically altered by the interruption of the electricity supply starting in autumn 2020. There is practically no data of an event of interruption of supply in an EU context, neither for informal settlements nor the general population. Finally, it constitutes a rare example of human rights-inspired energy research empirically assessing the material living conditions of populations with informal/irregular connections to the electricity supply in a Global North context.

In summary, this article aims to expose levels of precariousness that existing energy poverty surveys and datasets are often unable to observe and measure. The Cañada Real conditions cannot be captured by national and sub-national monitoring instruments such as the EU Survey on Income and Living Conditions (SILC) or national Household Budget Surveys. Consequently, we conduct case-specific research for which primary data was collected by the research team in field visits to Cañada Real during 2020 and 2021, and then analysed together with secondary data containing previously unreported data on the settlement. With this manuscript, we as co-authors make the case for the need of 'emergency research' with the aim of demonstrating "how energy research can be used as human-rights-based evidence [so that] the energy activities that violate human rights can be more readily targeted and prevented" [43].

3. Methods and data analysis

Most quantitative studies aimed at measuring the incidence of energy poverty and at assessing the living conditions of affected populations are based on large representative samples at a national or regional scale coming from datasets collected annually by national statistical offices such as the Household Budget Survey or the EU Survey on Income and Living Conditions (SILC). Consequently, there are few instances of survey-based research to quantitatively assess energy poverty at the city or district scale. Examples include Oliveras et al. [44] and Tirado-Herrero [45] for Barcelona, Spain; Castaño-Rosa et al. [46] for Sevilla, Spain; Petrova et al. [47] for Stakhanov, Ukraine; and Bouzarovski and Thomson [48] for eight districts in four Central and Eastern European cities. These studies usually work with data from random sampling and provide descriptive analyses together with multivariable statistics to identify the determinants of living in energy poverty conditions.

In this study, we conduct a quantitative assessment of the change in living conditions experienced by the population of Sector 5 and 6 of Cañada Real after October 2020. Following Sovacool et al. [49], we aim to address a socially relevant and impactful research question (What are key factors and characteristics of collective supply disconnections in relation to informal housing?) through surveys, quantitative data collection and data analysis that aim to produce new valid empirical evidence from an exceptional group/population (i.e., the case of Cañada Real residents). More specifically, we analyse an assemblage of primary and secondary quantitative data and analysis composed by: (1) primary data consisting of a 39-household energy survey and sensor-based voltage and indoor living conditions measurements collected by the research team in Sectors 5 and 6 through a series of 30 field visits to the settlement in the years 2020 and 2021; and (2) secondary data in the form of the 2014–2016 Cañada Real census provided by the Office of the

Commissioner for Cañada Real Galiana of the Government of the Community of Madrid. These data sources are described below.

3.1. Cañada Real census [dataset 1]

Census data for La Cañada Real as a whole (Sectors 1 to 6) were collected in 2014–2016 by the Social Housing Agency and the Office of the Commissioner for La Cañada Real Galiana of the Government of the Autonomous Community of Madrid. The dataset, which contains census data of 6663 people living in 1911 households, was anonymized, and made available to the authors for research purposes, by virtue of the collaboration agreement of September 29th, 2020, between the Community of Madrid and the Carlos III University of Madrid, to carry out the project 'Diagnosis of the energy uses and needs of the population of the Cañada Real Galiana'.

As a valuable secondary source, the census provides a complete sampling of the population of Cañada Real in 2014–2016. Being an informal settlement with relatively high mobility of residents, sociodemographic data for Cañada Real differ depending on the source. Yet the Cañada Real census is the most updated and accurate source in this regard.

3.2. Household energy survey [dataset 2]

Based on a non-probability convenience sample of Sectors 5 and 6 of Cañada Real, self-reported data on household energy issues was collected from 39 households in Sector 5 (18 surveyed households) and 6 (21 surveyed households) during 2020–2021. The households of the sample were selected among contacts obtained from a diversity of NGOs and social agents operating in the settlement (e.g., educators and social workers from the city council, local priest, neighbourhood associations, etc.). The response rate was high and >90 % of the contacted households contacted were interviewed. The questionnaire was completed by an adult of the household, generally the head of the family.

These data were used to analyse, with descriptive statistics, the impact of shutdowns on the energy metabolism of the households. Even if the 39-household sample cannot be seen as representative of the total population in these two sectors, the figures and percentages obtained (presented in the results section) are considered a fair indication of domestic energy use in this part of the settlement affected by post-October 2020 disconnections. The margin of error for a 95 % confidence interval for the results obtained from this sample (in an approximation that considers random sampling) is presented in Table 1.

3.3. Indoor living conditions [dataset 3]

Temperature data from a non-probability convenience sample of Sectors 5 and 6 of Cañada Real, was collected on a series of field visits during 2020–2021. Monitored households were selected among those that responded to the household energy survey questionnaire [dataset 2], trying to reflect the variety of household types, building condition and family budgets and characteristics. The response rate was around 70 %, as some households agreed to the survey but declined the monitoring. A variety of logistical problems concerning the sensors used for data collection throughout the monitoring period were reported, which resulted in several households withdrawing from the sample and then being substituted by newly recruited families. No incentives were offered for participation in the household energy survey or indoor living conditions monitoring – even if advice and an individual report on household ambient conditions was offered to those that agreed to participate the monitoring.

This primary dataset contains temperature records of the living room conditions of 12 households (5 in Sector 5, and 7 in Sector 6), acquired in 15-minute intervals between March and November 2021. Conducting sensor-based measurements in an informal settlement represents a serious challenge and a variety of incidences were detected, which affected the continuity of the measurements. Therefore, from an initial deployment of 13 sensors, 2 were never returned, 1 was lost, and some produced inaccurate, intermittent or partial measurements. To cope with those problems, some new sensors were deployed in replacement households of those that withdrawn. At the end of the campaign, a set of reliable measurements of indoor thermal conditions of 12 households in spring (May 9–June 9, 2021) and autumn (October 20–November 20) 2021 could be extracted and is presented in the results section. This is by no means a representative dataset but provides initial evidence on a complex problem in a difficult environment. Temperature data was acquired with a thermo-hygrometer Elitech RC-4HC with accuracies of ± 1 $^{\circ}$C.

Both temperature and voltage (see below) data based on direct measurements through devices installed in Cañada Real households were not treated as representative for the population of Sectors 5 and 6 but as indicative empirical evidence of the living conditions endured by residents with no or precarious access to the electricity supply after October 2020.

Table 1
Margin of error for a 95 % confidence interval of percentages from the 39-household energy survey.

Percentage results	Sector 5	Sector 6	Both sectors
0	2 %	2 %	1 %
1 %	5 %	4 %	3 %
10 %	14 %	13 %	9 %
25 %	20 %	19 %	14 %
50 %	23 %	21 %	16 %
75 %	20 %	19 %	14 %
90 %	14 %	13 %	9 %
99 %	5 %	4 %	3 %
100 %	2 %	2 %	1 %

Source: Own elaboration.

3.4. Continuity of electricity supply [dataset 4]

Primary data on the continuity of the electricity supply was collected by the researchers with voltage meters installed in two Cañada Real households (one in Sector 5, and one in Sector 6) with the aim of detecting the presence of electric voltage at the two investigated supply points. This dataset contained binary (0/1) data acquired in two-minute intervals between December 2019 and August 2021. The meters used to detect outages were designed and built by the research team for the purposes of this research based on a RS PRO-USB-3 voltage logger, enabling it to collect network voltage data when connected to a power outlet of the household.

It is worth noting that despite the limited size of the sample, the two meters introduced above are considered indicative of the global conditions in each sector, in view of the internal homogeneity of the supply disconnections in each sector and the structure of the local power supply network (as each sector is fed by only one electricity supply branch). An expert opinion presented by an appointed electricity surveyor in a court dealing with the Cañada Real case identified the reclosers (i.e., automatic circuit designed to interrupt momentarily the electricity distribution) installed by the DSO in autumn 2020 in the medium-tension line (15 kV) feeding Cañada Real as the likely reason for the supply interruptions ongoing since October 2020. In the expert's view, these reclosers located in the branches of entry to Sectors 5 and 6 acted as limiters setting a maximum current threshold lower than the line capacity. Since the total electricity demand of each sector (5 and 6) was above the capacity thresholds set by the reclosers, residents suffered from continuous outages, leading to the effective disconnection of both sectors from the supply [50,51]. For these reasons, the electricity supply access conditions for each sector are assumed to be homogeneous since outages affected the entire population of each sector (5 and 6) connected to each of the two supply branches.

It must be also noted that, in response to the new supply conditions created by the installation of the reclosers in autumn 2020, during 2021 Sector 5 community responded by self-organizing to limit their aggregated electricity demand through programmed partial outages. This way, by periodically cutting the supply to parts of Sector 5 (i.e., sets of households staying without electricity for a few hours each day in turns), they managed to adapt to the new supply regime and to enable relatively stable access to the electricity. These developments do not invalidate, however, outage measurements obtained from the sensor located in the Sector 5 household, which were believed to be representative of the long-term supply conditions experienced by any resident in this sector during the investigated period.

4. Results

This section is organized in two parts. In the first part (Section 4.1), the living conditions in Cañada Real prior to the supply interruptions started in October 2020 are described. In the second part (Section 4.2), the living conditions resulting from the supply disconnection are analysed.

4.1. Conditions before the October 2020 supply interruptions

4.1.1. Socio-economic characteristics

The Cañada Real census [dataset 1] included 6663 residents, representing 0.12 % of the total population of the Madrid region in 2015. As shown in Tables 2 and 3, the population of Cañada Real is markedly different from the average of the region, with more children, fewer elderly, and more non-Spanish citizens, especially Roma people and North African migrants. These figures speak of the origins and development of Cañada Real as an informal settlement that has traditionally attracted residents unable to access legal housing in the Madrid metropolitan area, who often belong to ethnic minorities. Within the settlement, Sectors 1 and 2 are predominantly inhabited by middle-aged and elderly Spaniards, with a low presence of Roma and foreign population. In contrast, Sectors 4, 5, and 6 display a higher percentage of children, foreigners (mostly Moroccan) and Roma.

Electricity supply interruptions ongoing since October 2020 have affected primarily Sectors 5 and 6 – the most populous section of Cañada Real hosting >60 % of the settlement's residents. However, this section of Cañada Real also has more complex population dynamics with regional social services having rehoused 130 families from Sector 6 since 2018.

Regarding the financial situation of the settlement's residents, Fig. 1 and Table 4 indicate that the median household income in all sectors was below the at-risk-of-poverty threshold, with 89 % of the population at risk of monetary poverty in 2015. Sectors 3, 4, 5, and 6 had the highest monetary poverty rates, and almost the entire population of these sectors was below the at-risk-of-poverty threshold. For a comparison, Eurostat reports a 22.1 % of the population at risk of poverty for the whole of Spain and a 15.1 % for the Community of Madrid in 2015 [55]. All in all, such figures describe Cañada Real as an informal settlement mostly inhabited by a population subject to severe income deprivation along with other forms of social exclusion.

Table 3
Socio-demographic data for Cañada Real Sectors 5 and 6.

		Sector 5	Sector 6
Households		393	616
Average household size (members per household)		4.07	3.79
Country or region of birth	Spain	47.2 %	68.5 %
	Morocco and other Northern African countries	46.0 %	25.0 %
	Romania and Bulgaria	4.0 %	5.4 %
	Latin America	2.2 %	0.5 %
	Portugal and other European Countries	0.2 %	0.6 %
	Other	0.4 %	–
Gender ratio (M/F)		1.02	1.01

Source: Cañada Real census [dataset 1].

4.1.2. Building typologies, housing quality, and overcrowding

More than half of Cañada Real residents (56 %) live in standard single-family households constructed by professional builders using proper building materials, as shown in Table 5. However, an unknown but significant number of these homes are self-constructed. Small multi-family buildings house 21.6 % of households, while substandard housing accommodates 10.6 % of households, with shacks built with waste materials housing 8.6 %. Housing quality was evaluated by an architect as part of the 2014–2016 census (Table 6), with practically all shacks, 81 % of substandard houses, and even 5 % of standard housing deemed to be in very poor condition. The data on Tables 5 and 6 provides additional evidence both on the generally poor conditions at Cañada Real and on the sharp difference between sectors 1–2, and sectors 3–6. The declining gradient usually attributed to La Cañada Sectors and shown previously in household income is not so evident in living conditions between Sector 3 to Sector 6, in part because of the existence of small, well-defined slum areas built after most of the sector and embedded in sectors 3 and 4.

Housing overcrowding is not a significant issue in Cañada Real, although the overcrowding index is increasing from Sector 1 to 6. Overcrowding ($2.5 \leq OI < 5$) occurs in 19 % of households in Sector 5 and 30 % in Sector 6, with critical overcrowding ($OI > 5$) affecting 5.8 % of households in Sector 6. Overcrowding in both Sector 5 and 6 is due to the shortage of independent bedrooms rather than the presence of large households (Fig. 2).

Table 2
Socio-demographic analysis of Cañada Real's Sectors 1 to 6 in 2016 (as a percentage of the population in each unit).

	Population (persons)	Age groups			Population with disabilities	Citizenship and ethnic background		
		Children (<18)	Adults	Elderly (>65)		Spanish citizens	Foreign citizens	Roma[a]
Sector 1	499	11 %	70 %	19 %	5 %	93 %	7 %	1 %
Sector 2	577	11 %	66 %	24 %	7 %	94 %	6 %	6 %
Sector 3	385	25 %	63 %	12 %	6 %	86 %	14 %	43 %
Sector 4	1268	32 %	61 %	7 %	3 %	67 %	33 %	39 %
Sector 5	1601	32 %	63 %	5 %	3 %	45 %	55 %	7 %
Sector 6	2333	34 %	62 %	4 %	3 %	66 %	34 %	50 %
Cañada Real (total)	6663	29 %	63 %	8 %	4 %	67 %	33 %	30 %
Madrid region	6,436,996	18 %	66 %	16 %	5 %	87 %	13 %	1.1–1.4 %

[a] The percentage of Roma includes both foreign and Spanish population.
Source: Socio-demographic data for Sectors 1 to 6 extracted from the Cañada Real census [dataset 1]; socio-demographic data on total and foreign population (2015) extracted from the statistical portal of the Autonomous Community of Madrid [52]; Roma population data for 2015 retrieved from the 'Plan for the Social Inclusion of the Roma Population of the Autonomous Community of Madrid 2017–2021' [53]; data on persons with disabilities (2015) retrieved from the portal of the Autonomous Community of Madrid government [54].

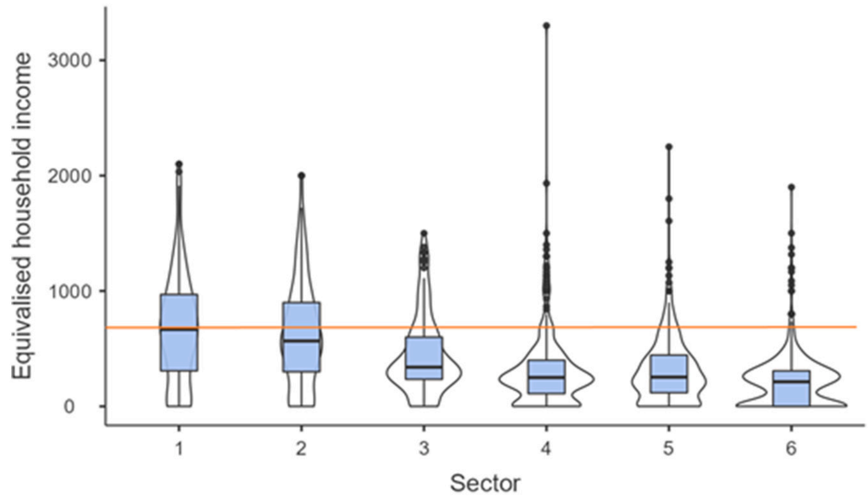

Fig. 1. Box plot of equivalised household income (€/month per consumption unit) and at-risk-of-poverty threshold line (684€/month per consumption unit) for the 6 sectors of Cañada Real.
Source: Cañada Real census [dataset 1].

Table 4
Equivalised household income distribution (€/month) and population below at-risk-of-poverty threshold.

Sector	Percentiles (€/month per consumption unit)			At-risk-of-poverty	
	25th	50th	75th	Population (%)	Households (%)
1	308	667	970	54 %	51 %
2	300	567	900	63 %	62 %
3	235	340	600	85 %	81 %
4	110	250	400	94 %	91 %
5	118	253	444	94 %	91 %
6	0	213	308	98 %	97 %

Source: Cañada Real census [dataset 1].

4.1.3. *Access to utility services and amenities*

Tables 7 and 8 show the dire conditions of Cañada Real residents before the power shutdowns in October 2020. In 2016, 93 % of households relied on irregular electricity connections, 91 % got their water from irregular connections, 48 % discharged wastewater to cesspools, and 95 % had no street lighting. These statistics evidenced widespread precariousness in the access to basic amenities and utility services in stark contrast with the full access conditions of the surrounding or nearby formal urban fabric in municipalities such as Coslada or Rivas-Vaciamadrid. When looking at differences within the settlement, only a relatively higher percentage of households living in the most consolidated Sector 1 had legal contracts with electricity and water suppliers, access to the sanitary sewer, and street lighting. All in all, most households of Cañada Real depended on insecure, irregular connections to the electricity and water supply before October 2020. Then, the October 2020 events resulted in a sudden and severe deterioration of living conditions for inhabitants in Sector 5 and 6, as they unexpectedly lost access to the electricity supply, creating an additional living conditions cleavage with Sectors 1 to 4. Note that 71.1 % of the settlement's children lived in Sectors 5 and 6 as of 2016, with Sector 6 alone accounting for 1211 children (47.5 % of the total), making the post-shutdown conditions particularly concerning for their health and well-being. These two sectors are also home to a significant number of Moroccan migrants and Roma people, which highlights discrimination and social exclusion patterns related to the ethnic and migration background of Cañada Real residents.

4.1.4. *Household energy equipment*

Data collected through the dedicated survey for a sample of 39 households (18 households in Sector 5 and 21 in Sector 6) [dataset 2] give a glimpse of how domestic energy use was before October 2020. As explained above (Table 7), most Cañada Real households lacked (and still lack) a legal connection to the electricity grid. In Sectors 5 and 6, survey data confirmed that 38 out of the 39 households (97 %) had

Table 6
Quality of residential buildings in the 6 sectors of Cañada Real (% of households).

	Very poor	Poor	Average	Good	No data
Sector 1		20.6 %	55.0 %	6.3 %	18.0 %
Sector 2	1.4 %	25.8 %	41.6 %	29.0 %	2.3 %
Sector 3	35.1 %	33.6 %	23.1 %	3.0 %	5.2 %
Sector 4	33.5 %	49.4 %	12.0 %	3.9 %	1.1 %
Sector 5	10.9 %	65.6 %	16.5 %	5.6 %	1.3 %
Sector 6					100.0 %
Total (sectors 1 to 5)	16.4 %	44.5 %	25.9 %	9.0 %	4.2 %

Note: no data available for Sector 6.
Source: Cañada Real census [dataset 1].

Table 5
Residential building typologies in the 6 sectors of Cañada Real (% of households).

	Warehouse	Shack	Caravan	Sub-standard housing	Prefabricated housing	Multi-family building	Standard single-family housing
Sector 1		0.5 %		1.1 %	2.1 %	51.9 %	43.9 %
Sector 2	0.5 %			0.9 %	4.1 %	23.1 %	71.,5 %
Sector 3	0.7 %	17.9 %	5.2 %	5.2 %	2.2 %	15.7 %	53.0 %
Sector 4	0.8 %	16.5 %		14.8 %	0.6 %	5.3 %	62.0 %
Sector 5		3.6 %		5.3 %	0.5 %	28.2 %	62.3 %
Sector 6	0.3 %	10.7 %	1.8 %	19.0 %	3.6 %	17.4 %	47.2 %
Total (all sectors)	0.4 %	8.6 %	0.9 %	10.6 %	2.2 %	21.3 %	56.0 %

Source: Cañada Real census [dataset 1].

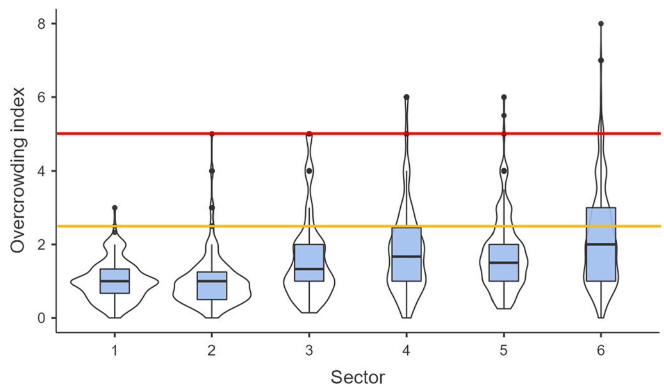

Fig. 2. Box plot of the overcrowding index for the 6 sectors of Cañada Real. Source: Cañada Real census [dataset 1].
Note: The overcrowding threshold is at 2.5 (orange line) and critical overcrowding (red line) happens when the index is above 5. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

electric power through informal connections, with the remaining one household from Sector 6 declaring to have no connection at all. Household survey data also indicated a clear preference for electrical space heating equipment because informal connections allowed them to get electricity for free (Table 9). Around 15 % (17 % in Sector 5 and 14 % in Sector 6) claimed not to have any electrical heating at all, while more than half of the 39 surveyed households (67 % in Sector 5 and 48 % in Sector 6) relied on oil radiators. Most households that did not have electrical heating (15 %) relied on fireplaces, firewood ovens or portable butane heaters, while only 23 % of the households had such non-electrical equipment as backup for those periods during which the informal local distribution grid failed and power went off. The remaining 62 % of surveyed households did not have any alternative means to electrical heaters and therefore could not cope with supply intermittencies, which were common well before October 2020.

Table 10 shows the availability of different appliances for communication, entertainment, personal hygiene, air conditioning and food storage and processing in the surveyed households. All households had TV (most times a quite large set) and fridge, and most had a washing machine and at least one mobile phone. A Wi-Fi connection, an air conditioning unit, and a food processor were sometimes present. A dishwasher or a freezer was only recorded in selected households. Dryers were seldom reported. Concerning cooking facilities, most households relied on electric stoves and ovens, although some had an LPG stove. These data confirm that, prior to October 2020, households in Sectors 5 and 6 relied on electricity for satisfying most of their domestic energy service needs, thus rendering them vulnerable to the long-term loss of supply that later occurred. Still, 46 % of the households also had some non-electrical equipment for cooking or heating (a butane cookstove, a fireplace, a butane heater, etc.), which was mainly used during supply interruptions.

4.1.5. *Continuity of electricity supply*

Data collected through voltage meters installed in two Cañada Real households [dataset 4] allow assessing the quality of the electricity supply in Sectors 5 and 6 before the October 2020 emergency. Typically, the quality of the electrical service is defined as the adequacy of the service according to certain characteristics that must be ensured by the DSO as a main feature of the quality of the network [56]. It is often

Table 9
Electrical equipment for space heating in La Cañada (% of surveyed households).

Sector	5	6
Heat pumps	6 %	24 %
Electric stoves	11 %	10 %
Thermal emitters	6 %	–
Oil radiators	67 %	48 %
Air heaters	17 %	38 %
Convectors	–	5 %
Other (e.g., electric brazier)	6 %	5 %
None	17 %	14 %
Number of different types of heaters per household	1.3	1.5
Total number of heater units per household	2.3	2.2

Note: The sum of percentages goes over 100 % because households often had diverse types of electrical heating equipment, as established in the last two rows of the table.
Source: Household energy survey [dataset 2].

Table 7
Conditions of access to the electricity supply and to street lighting by Cañada Real's sectors in 2015 (as a percentage of the population in each sector).

	Population (persons)	Electricity supply				Street lighting	
		Legal contract	Irregular connection	Solar panel	No supply	Available	Unavailable
Sector 1	499	68 %	29 %			68 %	32 %
Sector 2	577	11 %	87 %		0.3 %	1 %	99 %
Sector 3	385		99 %		0.8 %	1 %	99 %
Sector 4	1268		97 %		0.2 %		100 %
Sector 5	1601	0.1 %	100 %			0.2 %	99,8 %
Sector 6	2333	0.04 %	99 %	0.2 %	0.1 %	0.2 %	99,8 %
Total (all sectors)	6663	6 %	93 %	0.1 %	0.1 %	5 %	95 %

Source: Cañada Real census [dataset 1].

Table 8
Conditions of access to water supply and sanitation by Cañada Real's sectors in 2015 (as a percentage of the population in each sector).

	Population (persons)	Water supply					Sanitation		
		Legal contract	Tank	Irregular connection	Own well	No supply	Sanitary sewer	Cesspool	Without sanitation
Sector 1	499	70 %		27 %		0.4 %	80 %	16 %	0.4 %
Sector 2	577	10 %		88 %	1 %	0.2 %	91 %	7 %	1 %
Sector 3	385			98,7 %	1 %	0.3 %		92 %	4 %
Sector 4	1268		0 %	97 %	0.2 %		3 %	66 %	4 %
Sector 5	1601		1 %	98 %	0.4 %	0.4 %	78 %	17 %	0.5 %
Sector 6	2333		0 %						4 %
Total (all sectors)	6663	6 %	0.3 %	91 %	0.3 %	1 %	33 %	48 %	3 %

Source: Cañada Real census [dataset 1].

Table 10
Household appliances and electrical equipment (% of surveyed households).

Sector	5	6
TV	100 %	100 %
Mobile phone	94 %	95 %
Computer, laptop, or tablet	72 %	38 %
Internet connection	44 %	29 %
Fridge	100 %	100 %
Washing machine	100 %	90 %
Air conditioning	56 %	67 %
Dishwasher	33 %	19 %
Freezer	28 %	14 %
Dryer	6 %	5 %
Food processor	44 %	52 %
Other	11 %	0 %
Electric oven	67 %	67 %
Microwave oven	61 %	52 %
Electric vitroceramic stove	67 %	33 %
LPG/butane cookstove	33 %	14 %

Source: Household energy survey [dataset 2].

assessed through continuity of supply indexes that do not consider, however, aspects related to the quality of the wave (i.e., harmonics, flicker, over and under-voltages, etc.) [57]. From the perspective of the users, the quality of the service is assessed by the absence of power in the electrical devices plugged to the network, which translates as an interruption or supply outage. Problems in the electricity network can lead to a lack of continuity of electricity supply, in the form of either short (<3 min) or long interruptions. Continuity of electric supply metrics help assess the reliability of the electrical supply based on the number and duration of interruptions. In Spain, these indexes are called NIEPI (number of supply interruptions per year) and TIEPI (total duration of the outages)[1] [58]. They are calculated considering long (>3 min) interruptions and allow defining individual and zonal indexes of supply quality. NIEPI and TIEPI are the equivalent to the EU's System Average Interruption Frequency Index (SAIFI) and System Average Interruption Duration Index (SAIDI) [58,59]. For the purposes of this research, Cañada Real's NIEPI and TIEPI scores are assessed against the benchmarks set by Spanish regulation: a maximum of 12 interruptions and 9 h per year applied –-the legal maximum in Spain for a scattered rural distribution network, which is less rigorous than those that apply to an urban network.

Table 11 shows monthly values for both NIEPI and TIEPI indexes obtained from voltage meters installed in two Sector 5 and Sector 6 households between December 2019 and September 2020 [dataset 4]. Note that coloured cells indicate values above normative limits, with a lighter shade showing a situation of inadequate quality of the service where the 12 interruptions/9 h per year benchmarks are exceeded within the year (assuming that the tendency established for each month was maintained the whole year) and a darker shade for months with far poorer quality of supply scores (when the year benchmarks are exceeded in less than one month). In Sector 5, both NIEPI and TIEPI values are above the limits established by the Spanish regulation most of the time – but less until July 2020. Then, both the number of interruptions (4 to 8 times) and their total duration (50 to 60 times) greatly exceeded benchmarks. In Sector 6, both NIEPI and TIEPI values were significantly above regulatory benchmarks. December 2019 data show a far larger duration of interruptions in Sector 6 which is linked with a high electricity demand period around Christmas that results in longer and more numerous interruptions – an issue identified by Cañada Real residents as a recurrent problem also well before October 2020. In the Sector 6 household where data was retrieved, this means that electric power was out 71 % of the time during the Spanish Christmas holidays (from December 21st to January 6th). Overall, these results indicate that even before October 2020 Cañada Real households experienced much poorer reliability of electrical supply with NIEPI and TIEPI values well above benchmarks established by Spanish regulation and the average scores for the Autonomous Community of Madrid (1.22 interruptions/year and 0.92 h/year).

4.2. Conditions after the October 2020 supply interruptions

4.2.1. Interruptions of supply following DSO interventions

On October 2nd, 2020, interventions on the local electricity distribution network unilaterally implemented by the DSO resulted in a sudden, unannounced interruption of the supply in Sector 6 that later spread to Sector 5 in November 2020 (see Table 12). According to Sector 5 neighbours' association, these interventions consisted of the disconnection of a main power line to which both sectors are hooked up, allegedly to protect the supply of a nearby highway lighting system and petrol station, and the installation of an automatic circuit recloser (ACR) to protect a second power line also feeding Sector 5 and 6. While temporary outages recorded in previous months accounted for 3 to 7 % of the total time (20–50 h per month – see Table 11), during the first months of the emergency (October–November 2020 in sector 6, November 2020 in Sector 5), supply interruptions increased to 50–70 % of the total time. Then, from December 2020 on, Sector 6 went into full blackout, with no household able to reconnect the supply throughout the whole period until August 2021 (Table 12). The DSO claimed a daily attempt to reconnect the network, but, if any, supply stayed on for seconds or even fractions of seconds. Even though measurements presented in this article stopped in April 2021, the situation in Sector 6 remained unchanged as of spring 2023.

In Sector 5, reconnections occurred, and stayed for short periods, during January and February 2021, but households could only rely on electricity for a minimum of 16–18 % of the total time. During this period, households met and started cooperating to find a solution for damage minimization. The neighbourhood self-organized the management of their local distribution network, diminishing global electricity demand whenever possible and, when needed, allocating the power supply to 3 or 4 sections (auto-dispatch), and rotating from one to the next after a few hours, thus avoiding whole-sector blackouts by distributing electrical load in time. This has allowed Sector 5 residents to live with some access during high demand periods (winter) and with full access (although still under load self-management conditions) in medium- and low-demand periods.

Data presented in Table 12 for Sector 5 also show a reduction of the time without supply, from >80 % before March 2021 to <40 % afterwards, leading to a period with no cuts in August 2021. Since then, informal communitarian self-management has succeeded in preventing cuts almost completely. Sector 5 residents attribute such achievement to the seasonal reduction in electricity demand in spring and summer and to the increased awareness of the neighbourhood to prevent new power outages after which reconnection would be uncertain. Still, sensor data from 2021 to 2022 (not included in Table 12) indicates that Sector 5 reported 25 to 33 % of the time without energy during high demand periods (mostly in winter), but then they consist of planned interruptions under a controlled and previously agreed schedule.

The adaptation of Sector 5 to the new context of supply cut-off and line capacity limitation after October 2020 has been possible thanks to the powerful social and associative fabric of this section of the settlement. Residents of Sector 5 have successfully disciplined themselves to reduce their electricity consumption to the strictly necessary limits allowed by the reset of the recloser. Confidence and support to the neighbour's coordination group in charge of executing planned intermittent shutdowns of subsections or parts of Sector 5 was also necessary. This coping strategy was helped by the structure of the distribution network in the form of a simple radial net fed by a small number of

[1] In Spanish, *Número de interrupciones equivalente de la potencia instalada en media tensión* (NIEPI) and *Tiempo de interrupción equivalente de la potencia instalada en media tensión* (TIEPI).

Table 11
Number of interruptions (NIEPI) and their overall duration (TIEPI) per month in Sectors 5 and 6 from December 2019 until September 2020.

Month	Sector 5			Sector 6		
	NIEPI	TIEPI		NIEPI	TIEPI	
	interruptions	hours	% time (% total time)	interruptions	hours	% time (% total time)
December 2019	2	0.3	0.1% (34%)	14	150.9	21.5% (94%)
January 2020	2	1.7	0.2%	20	38.3	5.2%
February 2020	0	0	0.0%	19	20.9	3.2% (92%)
March 2020	5	1.3	0.2%	Spring 2020 COVID-19 lockdown (no data available)		
April 2020	2	2.5	1.0% (36%)			
May – June 2020						
July 2020	3	3.2	2.9% (15%)	NA	NA	NA
August 2020	4	40.1	9,3% (58%)	NA	NA	NA
September 2020	8	52.4	7.3%	7	20.9	3.0% (97%)

Notes: 1) Data collection measurements stopped during the COVID-19 lockdowns in spring 2020 due to the impossibility to access the Cañada Real households where voltage meters were installed; 2) coloured cells represent values above limits established by the Spanish regulation; 3) for a comparison, average NIEPI and TIEPI scores for the Autonomous Community of Madrid are 1.219 interruptions/year and 0.922 h/year; 4) the % time column identifies the percentage of the total measured time that the supply is interrupted. In some cases, the total measurement time did not correspond to the whole month, and then the percentage of the total month time when measurements were available is noted between brackets.
Source: Continuity of electricity supply data [dataset 4].

Table 12
Number of interruptions (NIEPI) and their overall duration (TIEPI) in Sectors 5 and 6 from October 2020 until August 2021.

Month	Sector 5			Sector 6		
	NIEPI	TIEPI		NIEPI	TIEPI	
	interruptions	hours	% time (% total time)	interruption s	hours	% time (% total time)
October 2020	13	48.6	6.5%	55	430.0	63.3% (91%)
November 2020	38	372.2	51.7%	16	506.4	70.3%
December 2020	10	399,6	98.0% (55%)	1	744	100%
January 2021	22	628.0	84.4%	1	744	100% (80%)
February 2021	15	554.6	82.5%	1	672	100%
March 2021	12	252.9	34.0%	1	744	100%
April 2021	0	0	0.0% (55%)	1	432	100% (60%)
May 2021	0	0	0.0% (60%)			

Notes: 1) Coloured cells represent values above limits established by the Spanish regulation; 2) For a comparison, average NIEPI and TIEPI scores for the Autonomous Community of Madrid are 1.219 interruptions/year and 0.922 h/year; 3) The % time column identifies the percentage of the total measured time that the supply is interrupted. In some cases, the total measurement time did not correspond to the whole month, and then the percentage of the total month time when measurements were available is noted between brackets.
Source: Continuity of electricity supply data [dataset 4].

community-owned transformers. Transparency in planning and executing partial cuts of Sector 5 via a shared phone chat group has been instrumental to maintain coordination and support. However, such a unique concurrence of circumstances and conditions could not be replicated in Sector 6, with a weaker social fabric, a higher number of transformers (many of them privately owned) far apart from each other and a linear electricity supply distribution configuration.

4.2.2. Changes in household energy equipment

Post-October 2020 emergency conditions forced Sector 5 and 6 residents to react as quickly as possible when outside temperatures began to drop. Average outdoor temperatures in Rivas-Vaciamadrid during autumn 2020 fell from 21 °C in September to 15 °C in October, 10 °C in November and then 6 °C in December. Also, October is historically the month of the year with the highest rainfall in the area. The main challenges and dilemmas faced by the affected population at that point were: (1) deciding whether to wait for a possible reconnection of the local distribution network or not; (2) changing to alternative (non-electric) space and water heating equipment; (3) changing to alternative (non-electric) cooking equipment; (4) providing indoor illumination; and (5) looking for alternatives to other domestic energy services provided by electrical appliances, mainly food conservation.

In the first few months after October 2020 a large part of Sector 5 and 6 population opted for minor changes by acquiring basic, cheap alternative equipment (e.g., butane cookstoves) while hoping for a quick resolution to the supply interruptions. Also, as depicted in Table 10, some households already had non-electric appliances as backup against previous temporary outages. But as time passed and temperatures dropped, searching for more durable solutions became urgent. Depending on household finances, some opted for diesel generators, solar PV panels[2] and batteries (sometimes stand-alone batteries, which they charged during the times of available power supply) to keep electrical equipment running and occasionally for very expensive heating; others opted for portable butane/LPG stoves for space heating and butane water heaters; and, finally, a number of households opted for firewood heaters. In this last case, quite a difference must be established between more affluent households that had already installed a traditional or a highly efficient closed fireplace and poorer households that opted for a traditional cast iron firewood stove as the most economical way for heating.

Data collected by the 39-household energy survey [dataset 2] allows tracking the availability of non-electrical domestic energy equipment in Sectors 5 and 6 before the October 2020 interruption of the supply (when such devices were used as a prevention against intermittent outages or for desired flexibility of equipment and energy carriers) and of equipment bought in response to the energy emergency (Table 13). Figures identify the percentage of households with each type of equipment, whether they bought it before or because of the emergency, together with the situation at the time when survey data were collected (March–June 2021). Especially pronounced was the increase in diesel generators (as one the few reliable alternative sources of electricity), butane/propane heating stoves and water heaters. The evolution of the situation from autumn 2020 to spring 2021 was the following:

- In Sector 5, 7 households (39 %) did not have any non-electrical equipment prior to October 2020, while the rest had 2.3 non-electrical appliances on average (with a maximum of 3 per household). Due to supply interruptions, by spring 2021 all households had non-electrical equipment even if not all of them had to buy new equipment (3 households did not buy anything new, but relied on non-electrical equipment acquired previously). The average number of non-electrical appliances per household in spring 2021 was 3.6 items, with a maximum of 9.
- In Sector 6, in contrast, 14 households (67 %) did not have any non-electrical equipment prior to October 2020, while the rest had 1.4 non-electrical appliances on average (again with a maximum of 3 units per household). Like in Sector 5, by spring 2021 all households had non-electrical equipment even if there were 4 households that did not have to buy anything new thanks to non-electrical equipment acquired previously. By spring 2021, the average number of non-electrical appliances per household was 2.8, with a maximum of 8. Note that on average Sector 6 households had fewer non-electrical devices than those in Sector 5, even when the outages have been historically more frequent in Sector 6 and thus households more dependent on non-electrical equipment.

Table 13
Percentage of households with non-electrical equipment before and after autumn 2020.

Equipment	Bought before October 2020	Bought after October 2020	Situation in spring 2021
LPG/butane cookstove	26 %	41 %	62 %
Diesel generator	18 %	38 %	56 %
Butane or propane heating stoves	15 %	36 %	46 %
Firewood stove	10 %	21 %	31 %
Butane water heater	3 %	15 %	18 %
Traditional open fireplace	8 %	5 %	13 %
Closed fireplace	5 %	5 %	10 %

Source: Household energy survey [dataset 2].

These rapid changes did not, however, allow people to keep off cold during the 2020–2021 winter. Responses to the 39-household energy survey question about people's ability "to keep their home adequately warm" (as one of the primary self-reported indicators of the EU Energy Poverty Observatory, EPOV), show that 97 % of the interviewed households (38 out of 39) declared to be unable to keep an adequate temperature at home. This result is likely influenced by a period of unusually low temperatures during snowstorm Filomena, which hit Cañada Real at the worst moments of supply interruptions (January 2021) when Sector 5 and 6 residents had barely had the time to adapt to the new conditions.

4.2.3. Indoor temperatures

In order to assess how supply interruptions affected thermal indoor conditions in Cañada Real, sensors were installed in 12 households located in Sector 5 and Sector 6 [dataset 2]. Indoor temperatures were monitored, and four indicative cases were extracted and are presented in detail. These cases correspond to four distinctive thermal indoor conditions in Cañada Real after October 2020. Even if the small size of the dataset prevents the generalization of these findings as representative of Sectors 5 and 6. Using such a small sample of households allows assessing indoor temperature measurements in detail and linking those with household characteristics. Sensors were placed in the living space where people spent most of their time, i.e., in the living room usually, which is also used as a bedroom in some households, and sometimes in the kitchen.

Table 14 shows the characteristics of these four households in terms of their indoor temperatures, continuity of the electricity supply, building type, household composition and monthly income. Households A and D illustrate intermittent electricity supply conditions in Sector 5 once the community self-organized the management of electrical loads in the local distribution network (see details in Section 4.2.1). Household B represents a fully disconnected Sector 6 household, while household C is one of the rare Sector 6 cases in which the electricity

[2] Prior to the shutdown, solar PV systems could seldom be spotted in the settlement. When the household energy survey was done in spring 2021, few months after October 2020, still very few households had opted for a long-term solution such as solar PV panels, Sector 5 and 6 residents preferred diesel generators when they had the financial means. Later, when the community realized that disconnections were there to stay, the number of solar PV installations on roofs (usually coupled with storage batteries) in Sectors 5 and 6 grew exponentially, aided by the availability of low-cost equipment provided by local distributors. As of spring 2023 it is very common to observe solar PV on roofs, even if their performance is sometimes limited due to the low quality of panels and inverters (quite often bought as second-hand equipment) and of their installation and maintenance.

Table 14
Characteristics of Cañada Real's Sector 5 and 6 households with monitored indoor temperature data for spring and autumn 2021.

Case	Sector	Electricity supply	Building type	Household composition	Household monthly income
A	5	Intermittent	Substandard housing	3 adults	1600 €
B	6	No supply	Shack/ substandard housing	2 adults, 1 child	NA (undeclared or informal economic activities)
C	6	Continuous	Shack/ caravan	1 adult, 2 children	622 €
D	5	Intermittent	Standard housing	2 adults	2250 €

Source: Indoor living conditions data [dataset 3].

supply stayed on after October 2020 thanks to being connected to a branch of the distribution line left unaffected by the October 2020 events.

Indoor temperature data were collected in spring (May 9–June 9, 2021) and autumn (October 20–November 20) 2021 once post-shutdown emergency conditions had become the current standard of living in the settlement. Note that fieldwork logistics did not allow collecting data during the first few months right after the start of supply interruptions. Consequently, the temperature dataset does not capture the harsher conditions of the 2020–2021 winter during which the January 2021 Storm Filomena brought the heaviest snowfall in Madrid since 1971.

Results presented in Fig. 3 (spring 2021) and Fig. 4 (autumn 2021) show the percentage of time during which indoor temperatures are outside the thermal comfort zone, as well as the distribution of temperature differences relative to comfort benchmarks, for the four households in Table 14. Two different thermal comfort benchmarks have been applied:

- Fixed temperature benchmarks at 17 and 27 °C – interval inside which thermal comfort is attained in the dwelling as established by Spanish legislation (Royal Decree 486/1997). Note that this is less stringent than the WHO guidelines that prescribe 18 °C as a minimum comfort indoor temperature.
- Adaptive temperature benchmarks based on comfort range IEQ_{III} from standard UNE EN 16798–1:2019 [60] that establish a moderate comfort range inside which indoor temperatures do not represent any health risk but may not guarantee comfort. According to this IEQ_{III} standard, indoor air temperatures should be in the range $0.33 \cdot T_{o,rm} + 18.8 – 5 \leq T \leq 0.33 \cdot T_{o,rm} + 18.8 + 4$, where $T_{o,rm}$ is the

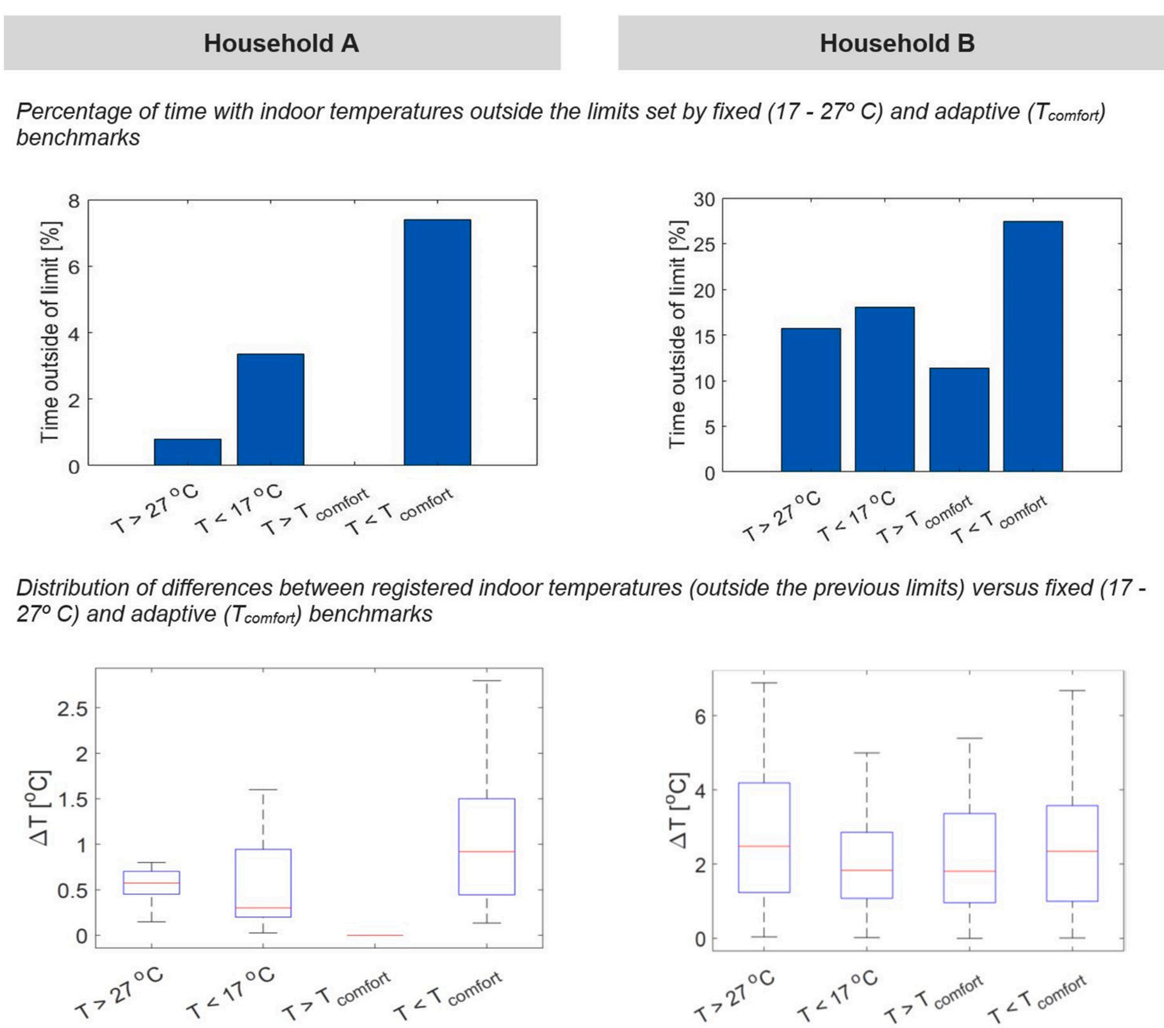

Fig. 3. Percentage of time outside thermal comfort conditions and distribution of temperature differences between registered temperatures and comfort benchmarks for households A, B, C and D in spring (May 9–June 9, 2021).
Source: Indoor living conditions data [dataset 3].

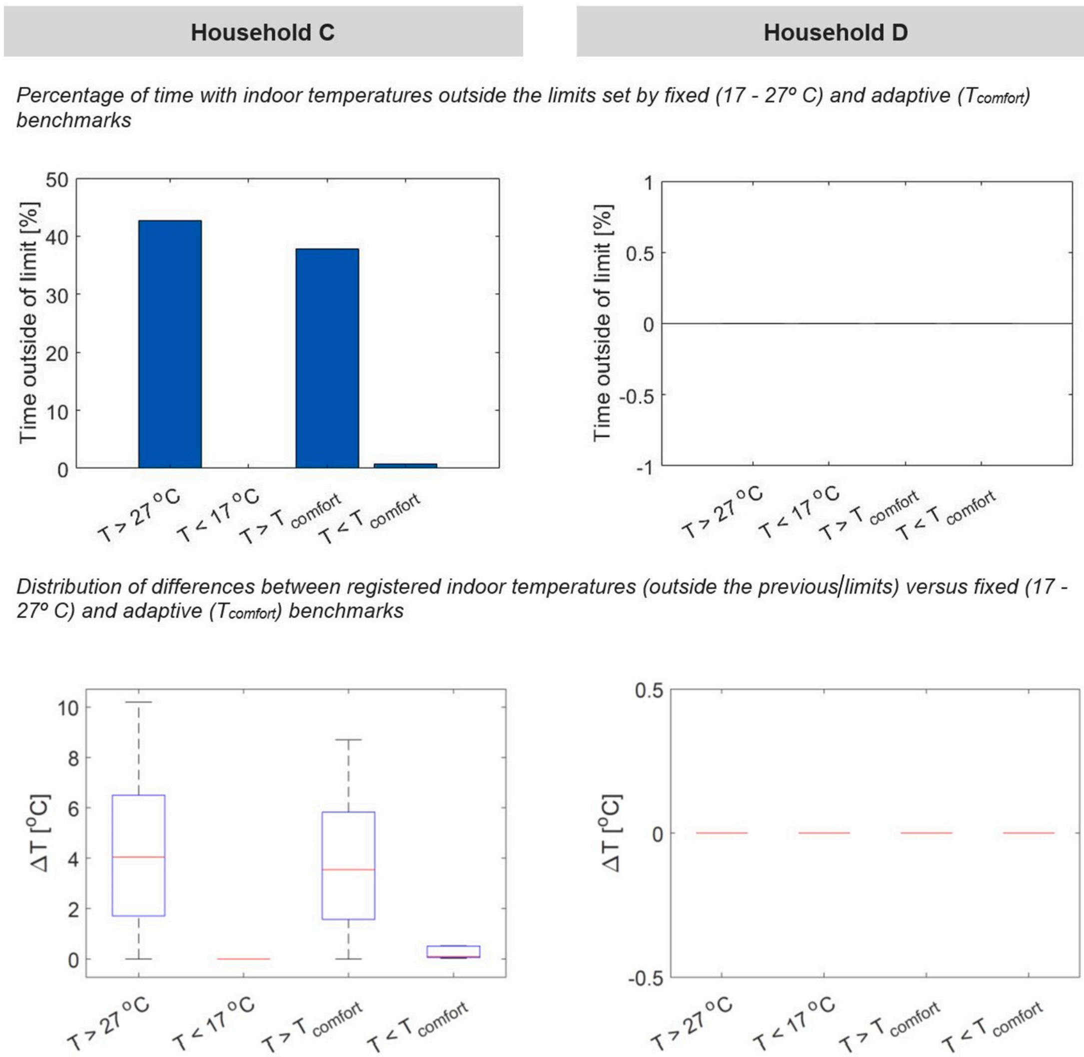

Fig. 3. (*continued*).

running mean outdoor temperature of the daily mean outdoor air temperature at a given location. For the calculation of this benchmark, outdoor temperature data for Cañada Real was obtained from the open database of meteorological stations of the Madrid Autonomous Community.

Figs. 3 and 4 provide results for both fixed and adaptive comfort benchmarks. Even if figures differ to some extent, both benchmarks provide similar evidence for each household. The following analysis primarily relies on fixed temperature benchmarks, with adaptive benchmark results only assessed when needed.

In spring 2021 (Fig. 3), three out of the four households registered indoor temperatures outside thermal comfort benchmarks – despite measurements being taken during the climatically mild period of May and the beginning of June. Specifically, households A, B and C recorded temperatures outside the thermal comfort zone during >4, 30 and 40 % of the time, respectively. In contrast, household D did not report temperatures outside the 17–27 °C range and therefore succeeded in keeping their home within a thermal comfort zone. Median excess temperatures (i.e., difference between registered indoor temperatures and benchmarks) were around ±0.5 °C for household A, around ±2 °C for household B, and around +4 °C for household C, meaning that half of the time that each household was outside the comfort zone, indoor temperatures were below 16.5 °C or above 27.5 °C in household A, below 15 °C or above 29 °C in household B, and above 31 °C in household C. These figures represent an acceptable situation in household A, where indoor temperatures were outside comfort during short periods; and worse conditions in household B, where uncomfortably high and low temperatures were recorded during far larger periods of time. Household C suffered from remarkably high indoor temperatures (above 31 °C for >20 % of the total time) but otherwise did not experience unsuitably cold temperatures.

Data presented in Fig. 4 for the autumn period (October 20th to November 20th, 2021) show that only temperatures below the cold threshold benchmark (17 °C) were reported. Unlike in spring, all four studied households had temperatures outside the thermal comfort zone in autumn. Households A and notably B represent the worst-case scenario, with temperatures below 17 °C during >45 and 80 % of the time, respectively. Median values of excess temperatures show that household A experienced temperatures below 16 °C during >20 % of the time, reaching temperatures as low as 12.5 °C in November 2021. Household B experienced temperatures below 12 °C during >40 % of the time, reaching temperatures as low as 5 °C. These represent harsh indoor conditions for the beginning of November, when weather conditions around Madrid are still mild. Unexpectedly, the shack of household C reported temperatures below 17 °C just 0.6 % of the time, while the well-constructed dwelling of household D experienced cold temperatures 1.5 % of the time. In both cases, median excess temperatures were below 1 °C. The adequate thermal comfort conditions of the household D can be explained by the better insulation and overall quality of the building, the

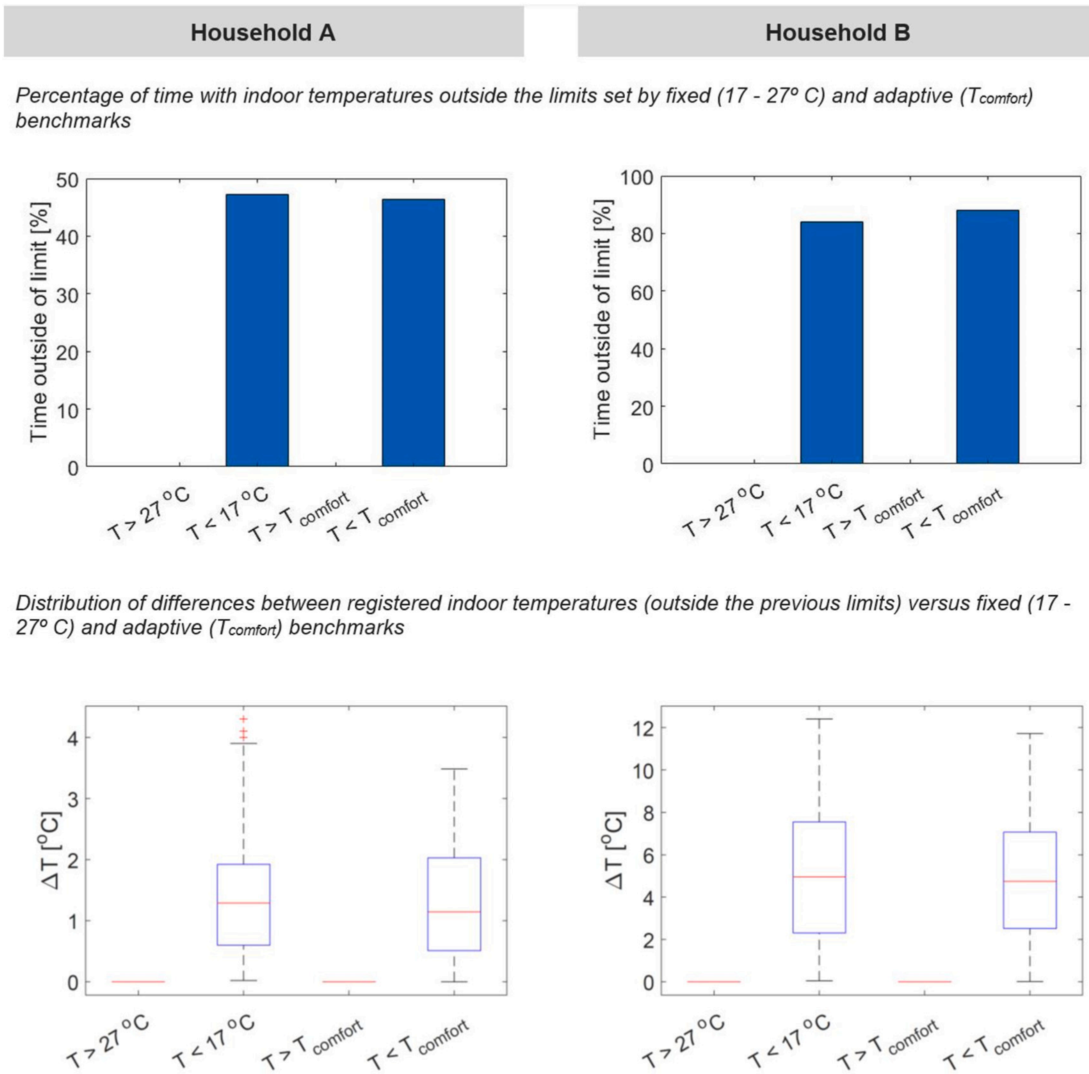

Fig. 4. Percentage of time outside thermal comfort conditions and distribution of temperature differences between registered temperatures and comfort benchmarks for households A, B, C and D in autumn (October 20–November 20, 2021).
Source: Indoor living conditions data [dataset 3].

presence of a well-designed fireplace, and the higher income of the residents (2250€ per month for two adults). On the other hand, the adequate indoor thermal conditions registered by household C (a substandard dwelling hosting a family of one adult plus two children reporting an income of just 630€/month) is likely explained by the fact that it was the only one of the four households that enjoyed uninterrupted power supply (thanks to being located in a specific Sector 6 spot unaffected by electricity cut-offs) and by the small dimensions of the shack, approximately the size of a caravan, which required less energy to stay warm inside.

The results obtained stress the importance of having a stable access to the electricity supply especially when living in substandard housing conditions. The comparison of households B and C is particularly telling in this regard. They both belong to the poorest-quality building category of the Cañada Real settlement. While they are both located in Sector 6, household C had continuous supply of electricity (thanks to being in a small area of Sector 6 where power remains available) and household B had been, like most of Sector 6, in total blackout during the monitoring period. Even if household C reported uncomfortably high indoor temperatures in spring 2021 (as they did not have any air-conditioning equipment), they managed to avoid cold in autumn thanks to their electricity-powered, low-cost radiative stove. This was not the case for household B, which remained fully disconnected from the supply throughout the whole monitoring period and registered extremely low living room/bedroom temperatures in autumn 2021. Household B represents the most vulnerable case among the four cases analysed as it was constituted by a young couple without any regular source of income and their few months old baby.

In Sector 5, household A lived in a substandard dwelling with a reasonable household budget, and household D inhabited a well-constructed building. They both 'benefited' from the intermittent supply conditions achieved by Sector 5 after spring 2021, which translated into better indoor thermal conditions overall.

As established at the beginning of this section, only four of the 12 monitored households have been analysed in detail. To assess the representativity of these four households within the overall dataset, Fig. 5 summarises the data presented in Figs. 3 and 4 and allows comparing the performance of households A, B, C and D with the remaining 8 units of the 12-household samples (labelled with the following numerals: 2, 4, 6, 7, 8, 11, 12, 14). The graphs present for each household the value of the percentage of time of the indoor temperatures outside fixed limits vs. the value of the median of the temperature

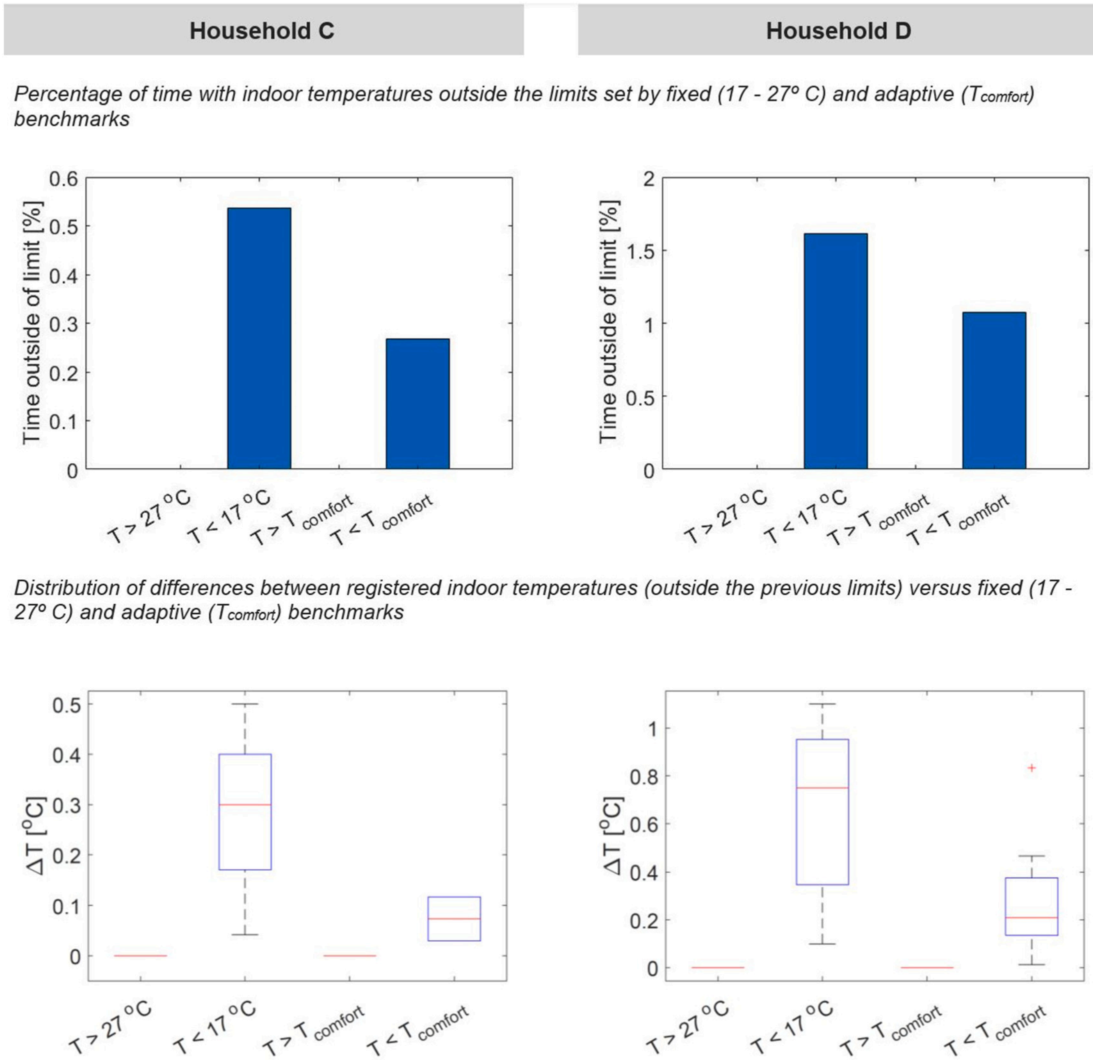

Fig. 4. (*continued*).

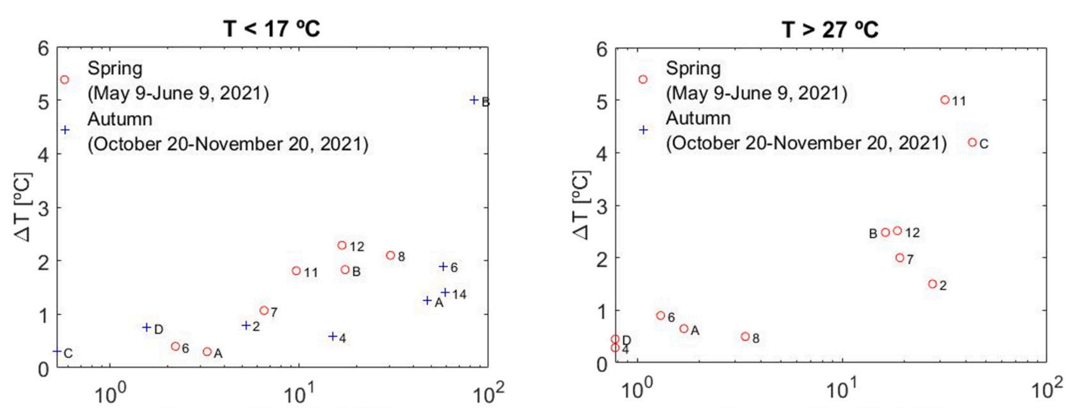

Fig. 5. Comparison of household temperatures outside thermal comfort conditions in view of percentage of time outside such conditions and the median of temperature differences between registered temperatures and comfort benchmarks for the 12 monitored households.
Source: Indoor living conditions data [dataset 3].

differences distribution for spring and autumn 2021.

Fig. 5 shows that the 12 households cluster in groups of high, medium, low or no incidence of thermal discomfort. Such clustering is detailed in Table 15, where the presented cases A, B, C and D are shown as representative of the other monitored households.

Overall, results give evidence of poor indoor thermal conditions for large periods of time in Cañada Real households affected by supply interruptions. Limitations in the dataset due to the challenges of

Table 15
Grouping in view of thermal discomfort of Cañada Real's Sector 5 and 6 households with monitored indoor temperature data for spring and autumn 2021. Note: Bold letters and bold figures represent Sector 6 households; the rest are Sector 5 households.

	Incidence	Spring		Autumn	
T < 17 °C	High	–	–	**B**	–
	Medium	**B**	**8**, **11**, **12**	A	**6**, 14
	Low	A	**6**, **7**	D	2, 4
	No incidence	**C**, D	2, 4	**C**	–
T > 27 °C	High	**C**	**11**	–	–
	Medium	**B**	2, **7**, **12**	–	–
	Low	A	**6**, **8**	–	–
	No incidence	D	4	A, **B**, **C**, D	2, 4, **6**, 14

Source: Indoor living conditions data [dataset 3].

conducting sensor-based measurements in an informal settlement only allow comparing data in the mild climate periods of spring and autumn 2021. Moreover, the measurements took place a few months after October 2020 once Sector 5 and 6 residents had already adapted to the new conditions (e.g., by installing firewood stoves or butane gas heaters). It is likely that conditions were more dire in the months immediately following October 2020 (especially the 2020–2021 winter season). In addition, considering the continental climate of the Madrid region, with low temperatures in winter and high temperatures in summer, indoor thermal comfort in Cañada Real households surely worsens during those seasons. This said, the data presented suggest a diversity of conditions, with some households feeling the brunt of supply interruptions much more than others depending on the quality of their dwelling, the availability of electricity (even if under intermittent supply conditions), the vulnerability of household members, and the resources they could mobilise in response to disconnections.

5. Discussion and conclusions

Energy poverty scholarship in Europe has been primarily concerned with indoor thermal comfort and the affordability of domestic energy services, even if a strand of the literature has also investigated issues of access to the supply through the lens of disconnections and irregular connections [61–63]. As previous research has focused on electricity supply interruptions at the individual household level, little is known about cases of collective disconnections of whole communities, with some exceptions –see Stojilovska [33] on the role of Ombudspersons in addressing neighbourhood-scale disconnections in North Macedonia. We address this gap by providing a range of previously unreported evidence about a salient, recent example of an intentional disruption of the electricity supply affecting a whole community within an affluent European metropolitan region: the case of Cañada Real Galiana (Madrid, Spain). For years, a large majority of residents in this informal settlement had received their electricity through informal connections to nearby power distribution lines up until October 2020, when technical changes introduced unilaterally by the DSO (allegedly on the basis of security concerns about the stability of the distribution network) effectively disconnected from the electricity supply 4000 people, including >1000 children (60 % of the settlement's population, living in Sector 5 and Sector 6), without any prior warning. Since then, the Cañada Real shutdown has been widely reported in Spanish and international media but had not yet been subject to scientific inquiry.

Against this background, this research contributes to fill a gap in the energy poverty and justice literatures on the topic of domestic energy deprivation in informal settlements. It investigates Cañada Real as a collective disconnection case of unprecedented magnitude in Europe that, as unique as it may seem, is indicative of the living conditions endured by other informal settlements in Europe with similar issues of insecure, irregular access to basic utility services linked to informal housing and lack of legal tenure of land and property. The research follows an emergency research approach that assesses previously unreported secondary census data on the socio-demographics of the Cañada Real [dataset 1] and, most importantly, a set of primary data collected by the researchers constituted by: a household energy survey [dataset 2], direct indoor temperature measurements [dataset 3] and continuity of electricity supply data [dataset 4] retrieved from a sample of households affected by supply interruptions. This evidence sheds initial light on the topics of collective disconnections and informal settlements and highlights an urgent need for further investigation of these areas (e.g., What is the lived experience of people living under collective disconnection conditions, and what are the impacts on health and well-being? Which energy and non-energy factors explain collective disconnections?) neglected by current energy poverty research and policies.

A main contribution of this study is exposing and documenting the precarious conditions of a community living with no or precarious access to the electricity supply because of the October 2020 events. Primary data on the continuity of supply collected by authors through voltage meters installed in Cañada Real households demonstrate that residents in Sectors 5 and 6 (the poorest half of the settlement) had to go without electricity for most of the time from October 2020 to March 2021. While continuity of supply rates as measured by NIEPI and TIEPI indicators, improved in Sector 5 after March 2021 (through self-organized collective action that had successfully managed to keep the sector's total demand under disconnection thresholds), the whole Sector 6 still remains without electricity as of summer 2023 and has no prospect of reconnection in the foreseeable future. Before the disconnection from the electricity supply, electrical heating equipment was the preferred option in the settlement. Affected households have partially adapted to the new conditions by replacing electric appliances with cheap but inefficient and polluting domestic energy technologies (e.g., butane gas heaters, firewood stoves, candles, etc.). As time passed and temperatures dropped, some households opted for diesel generators and/or batteries to keep electrical equipment running; some opted for butane/LGP stoves for heating and butane water heaters; and others for firewood heaters. Sector 5 could cope with the supply interruptions caused by the installation of the reclosers by reducing the demand and accepting a disconnection schedule in periods of high demand. Still, an evident negative outcome of supply disruptions is the widespread feeling of insufficient indoor thermal comfort among affected communities. The 39-household survey carried out by authors in spring 2021 resulted in 97 % of respondents stating their inability to keep their homes adequately warm during the 2020–21 winter – a perception likely exacerbated by the experience of storm Filomena (7–15 January 2021) in which the Madrid region registered the heaviest snowfall since 1971 and historically low (below zero) temperatures. Poor thermal comfort in Cañada Real dwellings has also been investigated by direct measurements of indoor temperatures through sensors installed by the research team in a sample of 12 households living in Sector 5 and 6. This dataset indicates significant percentages of time with temperatures outside indoor comfort ranges in spring and autumn 2021, with some instances of extremely low indoor temperatures in a household with a new-born baby (see Section 4.2.3). These conditions surely have dire consequences on vulnerable residents of Cañada Real because living with no or precarious access to energy is known to endanger human health and well-being [44,64].

Collective disconnections are having a differential impact on the vulnerable populations of the settlement. As of 2014–2016, over 1000 children lived in Sector 5 and Sector 6 (out of a total population of nearly 4000 in these two sectors). Clues about the impacts of October 2020 shutdowns on the underage population are provided by a survey report produced by Cañada Real's dwellers and activists that denounces an increased incidence of colds, mental health impacts, accidents related to the use of solid fuels at home, decreased school performance and instances of bullying against affected children [65]. Since child care is often provided by women, who are also responsible for many of the domestic energy services disrupted by the collective disconnection (i.e., food purchase, storage and processing; personal hygiene and cleanliness; entertainment, communication and education), Cañada Real hints at the gendered nature of the burdens imposed by energy poverty, in line with previous research on the topic [66–68]. Beyond those direct impacts, disconnections are also deepening pre-existing precariousness. Data from the Cañada Real's census reveal that as of 2014–2016 over 90 % of households in Sector 5 and Sector 6 earned below the monetary poverty line and relied on an irregular connection to the water supply network. Many also lived in inadequate housing (poor or very poor housing according to the census) and had no access to street lighting or sanitation. The set of evidence that we bring forward with this article highlights domestic energy and electricity supply disconnections as main drivers of the worsening of the 'slum-like' conditions endured by Cañada Real dwellers as described by previous research [69,70], which was surely exacerbated by the restrictions and additional difficulties imposed by the COVID-19 pandemic. The fact that most residents in Sector 5 and Sector 6 have a Roma or Moroccan background adds an ethnic layer to this complex picture, and highlights race as an explanatory factor of such instances of deep material deprivation in informal settlements, as advanced by Gonick [71] and Babourkova [31].

All in all, the range of evidence compiled in this article gives proof of Cañada Real as a case of 'extreme energy poverty', that is, "situations in which households have no reliable access to grid-based electricity despite the availability of a modern grid *in situ* or in proximity, on the account of coalescing factors beyond the common mix of poor infrastructure, fuel cost and low incomes" [32, pp. 1–2]. As predicted by these authors, current energy poverty metrics and measuring frameworks, which assume a legal energy supply contract, fail to represent extreme forms of energy poverty linked to informal, irregular access to the supply. In such contexts, indicators on access and reliability of the supply used in Global South studies may provide a better ground for assessing life conditions in locations such as Cañada Real.

There are, however, limitations and caveats in this study related to the difficulties of conducting research in a segregated and severely deprived community during the COVID-19 pandemic. Involving households affected by disconnections in the research was the main challenge for obtaining the necessary primary data for the analysis. Results coming from small samples need to be carefully considered and interpreted also in the light of the complex living conditions experienced by households that contributed to data collection. This means that results should also be understood as indicative of the need for further research and policy interventions to address energy poverty conditions endured by residents living in informal settlements without secure access to basic utility services.

From a policy/politics perspective, the Cañada Real case exposes the ways in which having secure access to the energy supply is highly conditional on formal housing arrangements. Cañada Real dwellers are not denied access to electricity because they are unable to pay energy bills on time or are indebted to providers. In their case, living in irregular housing means that they have historically relied on 'illegal' connections to the distribution grid, and therefore could be shut off by the DSO any time and without prior notice as it happened in October 2020. Existing legislation marginalizes Cañada Real dwellers as non-compliant customers that do not have any reconnection or vulnerable consumer protection rights, unlike what happens with regular 'legal' consumers disconnected due to the late payment or non-payment of utility bills. The only chance for Cañada Real people is some form of collective reconnection through political negotiation involving key stakeholders. In fact, the Cañada Real 'energy emergency' appeals to the various actors effectively capable of putting an end to ongoing supply disruptions, if only by restoring supply access to pre-October 2020 conditions. The list includes, first and foremost, the government of the Autonomous Community of Madrid, as main sponsor of the Regional Agreement for Cañada Real Galiana [38], and the Naturgy Energy Group, as parent company of the DSO in charge of the local distribution grid to which Cañada Real residents are (or were) irregularly connected. It also calls upon various national ministries (i.e., Ministry of Social Rights and 2030 Agenda; Ministry of Transport, Mobility and Urban Agenda; Ministry for the Ecological Transition) as well as the municipalities in which the Cañada Real settlement is administratively located (Coslada, Madrid, Rivas-Vaciamadrid and Getafe) that bear responsibilities for electricity sector regulation, housing policy, land tenure and social welfare provision. The Spanish government set up an inter-ministerial working group in September 2021 in response to a specific inquiry on Cañada Real submitted by the UN's Special Rapporteur on extreme poverty and human rights, Oliver De Schutter [72,73]. The working group has met on several occasions and committed a 5 million Euro national budget line for re-housing Cañada Real families "in situations of extreme social vulnerability" [74], but so far has not delivered any tangible results for addressing supply disconnections.

Lastly, a final word about the normative dimensions of the Cañada Real case study. Even if the actual living conditions in the settlement are a main concern of this work, in line with mainstream scholarship that sees energy poverty primarily as a form of material deprivation, we are also aware of the relevance of emerging research around dignity – and the related notions of respect, self-respect, and self-determination [75] – for this case study. This latter perspective, which is often present in public statements by Cañada Real residents in demonstrations and advocacy work, highlights the less tangible, but surely crucial, ethical dimensions and emotional burdens of life without electricity in one of the wealthiest regions of Europe.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share the Census data presented as Dataset 1. The rest of the data will be made available on request.

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