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Data Descriptor

Measured Indoor Environmental Data in a Retrofitted Multiapartment Building to Assess Energy Flexibility and Thermal Safety during Winter Power Outages

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Abstract: The article describes detailed measurements of indoor environmental parameters in a multiapartment housing block located in Milan, Italy, which has recently undergone a deep energy retrofit and is used as a thermal battery during the winter season. Two datasets are provided: one refers to a series of experimental tests conducted by the authors in an unoccupied flat, in which the thermal capacity of the building mass is exploited to act as an energy storage. The dataset reports, with a time step of 10 min, measurements of air temperature, globe temperature and surface temperatures in the analyzed room and data characterizing the adjacent spaces and the outdoor conditions. The second set of data refers to the air temperature monitoring carried out continuously in all the apartments of the apartment block, and hence also during two unplanned heating power outages. The analyzed data show the role of deep renovations in extending the time over which a building can remain in the thermal comfort range after an energy interruption and thus highlight the potential role of retrofitted buildings in delivering energy flexibility services to related stakeholders, such as the occupants, the building manager, the grid operator, and others. Furthermore, the dataset can be used to calibrate an energy simulation model to investigate different demand-side flexibility strategies and evaluate thermal safety under extreme weather events.

Dataset: https://doi.org/10.17632/b63c2gtynh.1.

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Keywords: air temperature; globe temperature; surface temperature; operative temperature; demand-side flexibility; heating power outage; deep energy retrofit; thermal mass; thermal safety; thermal comfort

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1. Summary

Building renovation is a key element in the EU's plans to reduce emissions by at least 55% by 2030 and to reach climate neutrality by 2050. The Renovation Wave for Europe [1], presented in 2020 by the European Commission, states the objective to at least double the annual energy renovation rate of residential and non-residential buildings by 2030 and to foster deep energy renovations. However, the rate of the energy renovation currently stands only at 1% per year, and in particular, deep renovations which reduce the energy consumption by at least 60% are carried out in Europe only in 0.2% of the building stock per year.

The challenges that hinder the diffusion of energy renovations have long been investigated in the research [2–7] which indicates, especially in residential buildings, the insufficient information on the potential benefits of renovation and lack of trust in the actual energy savings among the top barriers [8].

Energy retrofits can bring multiple advantages in addition to reduced energy use [9,10], such as healthier indoor environments, increased thermal comfort, improved productivity and overall quality of life, better integration of renewables, energy flexibility, climate resilience, reduced maintenance needs, and ameliorated interconnections within the district. Building stakeholders perceive the benefits from different perspectives: e.g., if building owners are primarily interested in generating returns from their properties, for residents, the most powerful factor is their direct experience of improved housing and greater comfort [11].

In the literature, several studies on energy retrofits focus on showing, beyond the energy savings, the effects of renovation measures on thermal comfort and indoor air quality, both via simulation models [12–14] or based on measured data [15–18]. There is growing interest in analyzing the effects of energy retrofits on the integration of renewable energy [19] and the behavior of retrofitted buildings under future weather scenarios to consider climate change impacts [20–22], analyses which are carried out through energy simulations. More recently, the potential of retrofitted buildings in providing energy flexibility via exploitation of thermal capacity of the building fabric (also called thermal mass) has been highlighted both via simulation models [23,24] and, to a lesser extent, measured data [25,26].

In particular, Erba et al. [25], after highlighting scarcity in measured data, focused their research on experimentally quantifying the effect of a deep renovation in increasing the performance of a building's thermal mass in acting as an effective thermal energy storage (TES) during winter that is able to deliver flexibility of demand, which is increasingly required by the grid or for self-consumption of locally generated renewable energy, and to guarantee thermal safety under extreme conditions, such as a power outage.

This data paper describes the datasets on which the study by Erba et al. [25] is based, gives details of the experimental procedure in order to allow replication by other researches and provides measured data, regarding:

- flexibility achieved thanks to thermal storage (in winter) in the building fabric of a building with a very good thermal envelope as a result of a deep retrofit;
- thermal safety assessment in a whole multi-apartment block;
- verification of the appropriateness of using air temperature as a proxy of operative temperature as a comfort parameter in the specific case study;
- full measurements of boundary conditions (temperatures of thermal zones adjacent to the one under study, weather data including solar irradiance).

These data can be useful for academics, engineers, energy modelers, in several study areas such as:

- the development of demand-side flexibility strategies of a single building and for preliminary design of a Positive Energy District;
- studies on future implications of the expected electrification of most or all energy uses in buildings;
- the creation of quality data for calibration of BEMs (Building Energy Models);
- a better quantification of co-benefits of deep retrofit of existing buildings.

The paper is structured as follows: Section 2 describes the databases; Section 3 presents the methodology of data collection and data processing; Section 4 reports examples of the information contained in the databases; Section 5 presents the conclusions.

2. Data Description

This paper provides two datasets in the form of excel spreadsheets which contain raw data of indoor environmental parameters measured during the winter season in a deep retrofitted housing complex, located in Milan. Furthermore, the measured values of air temperature, relative humidity, and global horizontal solar irradiance are provided to characterize the outdoor environment. Table 1 synthesizes the main information regarding the databases.

Table 1. Database information.

Specific subject area	Measured building indoor environmental data, building thermal behavior, energy flexibility measures, thermal comfort, thermal safety.
Type of data	Two databases in spreadsheet format (.xlsx): 1. Raw experimental data of the flexibility tests realized at flat level; 2. Raw field data during the unplanned energy supply interruptions at building level.
Data source location	City/Town/Region: Milan, Lombardy. Country: Italy.
Climate	Cfa according to Köppen climate classification.
Related research article	S. Erba, A. Barbieri, Retrofitting Buildings into Thermal Batteries for Demand-Side Flexibility and Thermal Safety during Power Outages in Winter. Energies, 2022 [25].

The first dataset, named ”Experimental data_Flexibility tests_Flat level”, refers to the measurements conducted in one unoccupied apartment of the building complex in which the authors have carried out a series of experimental tests under controlled conditions. The experiments, which are explained in detail in the paper by Erba et al. [25], consist of measuring the evolution of the indoor air temperature during the charging and discharging of the storage medium, i.e., the building thermal mass, in order to be able to assess the number of hours the building can remain in a specified comfort range without active energy input.

The second dataset, named “Field data_Unplanned energy interruptions_Building level”, reports the measurements of the indoor air temperature in several apartments of the housing block during two real cases of heating power outage that lasted several days each.

2.1. Case Study Description

The data have been collected in a public residential housing complex consisting of two L-shaped buildings with four stories each and a total of 66 flats. The two housing blocks are located in Milan, Italy, and have recently been retrofitted.

The retrofit had the objective of significantly reducing the “energy needs for heating and cooling” while maintaining and improving comfort conditions for the inhabitants.

The opaque part of the building façade and the slab separating the apartments from the uninhabited space under the tile roof have been externally insulated with 0.25 m of mineral wool, resulting in U-values of 0.13 W/(m^{2}K) and 0.15 W/(m^{2}K), respectively. The exposed ground floor slab has been externally insulated with 0.10 m of phenolic resin, resulting in a U-value of 0.22 W/(m^{2}K). The existing windows have been substituted with low-e double glazing windows and frame with thermal break (U_w equal to 1.66 W/(m^{2}K), g-value of 0.52). Extreme care has been devoted to the reduction of all thermal bridges. An exterior solar shading (motorized louvres manually operated by occupants) has been installed on each window (Figure 1).

The flat under investigation (F2), shown in Figure 2, has a net floor area of 62 m^2, exterior facing envelope area equal to 91 m^2, and an S/V ratio of 0.44. It is characterized by an L shape: the living room and the kitchen are southeast-facing, one bedroom and the bathroom are southwest-oriented, while the second bedroom is northwest-facing. At the northeast side of the flat, the kitchen is adjacent to the unheated staircase, while the other two sides of the flat are adjacent to a flat which was unoccupied (and thus unheated), during the tests performed in the 2021–2022 winter season. Above and under the flat there are another two occupied and heated apartments. The building is equipped with double flow mechanical ventilation, but at the time of the tests, the ventilation system operated only in extraction-mode with a flow rate of 0.13 ACH.

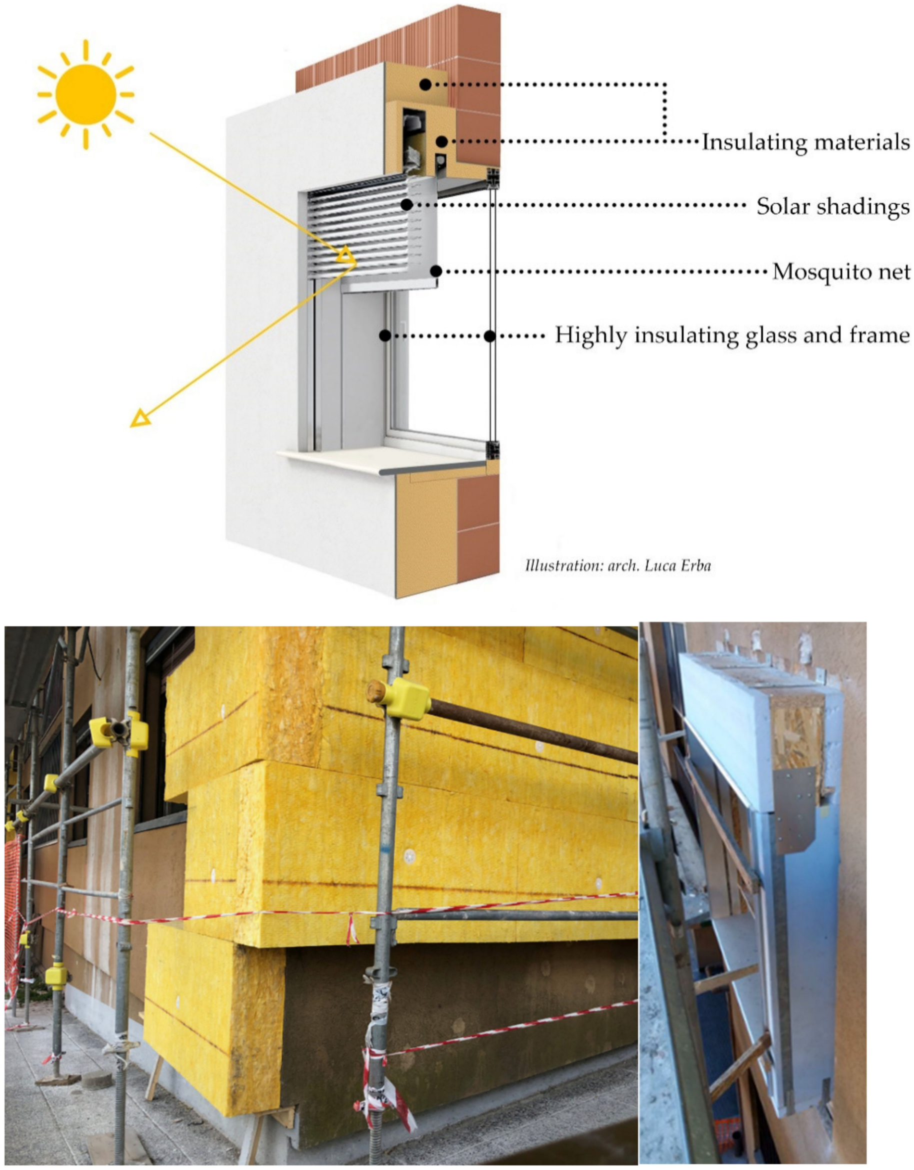

Figure 1. Image of the 25 cm thick external insulation; detail and photo of the window-wall node after the retrofit.

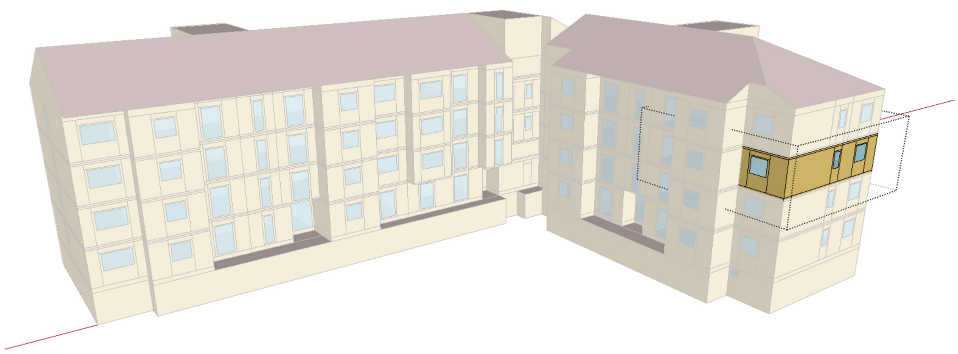

Figure 2. Localization of the flat in which the authors have conducted the flexibility tests.

2.2. Database 1: Experimental Data in the Test Apartment during the Flexibility Tests

The Excel file available as a supplement to this paper, "Experimental Data_Flexibility tests_Flat level", contains the following data, measured from 16 January 2022 to 10 April 2022:

- Time (column A);
- Living room air temperature at 1.7 m above the floor (Tair_room_1.7—column B);
- Globe thermometric temperature of living room (Tglobe_room—column C);
- Living room air temperature at 1.1 m above the floor (Tair_room_1.1—column D);
- Living room surface temperatures such as:
    - The wall adjacent to the bedroom (Ts_Wall_R—column E);
    - The wall along the hallway (Ts_Wall_Hall—column F);
    - The wall adjacent to the kitchen (Ts_Wall_L—column G);
    - The window (Ts_Window—column H);
    - The wall next to the window (Ts_Wall_W—column I);
    - The floor (Ts_Floor—column J);
    - The ceiling (Ts_Ceiling—column K);
- Bedroom1 air temperature (Tair_ind1—column L);
- Bedroom2 air temperature (Tair_ind2—column M);
- Bathroom air temperature (Tair_ind3—column N);
- Kitchen air temperature (Tair_ind4—column O);
- Entrance air temperature (Tair_ind5—column P);
- Stairwell temperature (Tair_adj1—column Q);
- Downstair flat (Tair_adj2—column R);
- Flat upstairs (Tair_adj3—column S);
- Adjacent flat (Tair_adj4—column T);
- Outdoor air temperature (Tair_out—column U);
- Global horizontal solar irradiance (Gs—column V);
- Relative humidity of the living room (RH_room—column W);
- Outdoor relative humidity (RH_out—column X).

2.3. Database 2: Field Data in the Apartments during the Unplanned Energy Interruptions

The Excel file available as a supplement to this paper, "Field data_Unplanned energy interruptions_Building level", contains the data measured in several apartments of the two apartment blocks during two real energy supply interruptions which affected, for several days each, the central heating plant serving both buildings. The first event occurred from 7 to 12 January 2022 and the second from 9 to 15 February 2022. Unoccupied flats were excluded from the analysis since they were unheated, and apartments where anomalies in data acquisition occurred were excluded as well. The spreadsheet is structured as follows:

- Sheet "January event":
    - Time (column A);
    - Global horizontal solar irradiance (Gs—column B);
    - Outdoor air temperature (Tair_out—column C);
    - Air temperature of the flats during January power outage event (N°Apartm-zone—from column D to column AN);
- Sheet "February event":
    - Time (column A);
    - Global horizontal solar irradiance (Gs—column B);
    - Outdoor air temperature (Tair_out—column C);
    - Air temperature of the flats during February power outage event (N°Apartm-zone—from column D to column AU).

3. Methods of Data Collection and Processing

Figure 3 reports the steps followed in the study to collect and process the data in an ordered and systematic way before starting the analyses. After the definition of the method (Section 3.1), the design of the experimental setup has been determined according to international standards. The number of parameters measured in the single test apartment (Database 1) is significantly higher with respect to the number of variables measured in every apartment of the whole building complex (Database 2). The description of the variables, the measurement equipment and details about data collection are provided in Section 3.2. Section 3.3 describes the procedure followed for data cleaning and processing, while Section 3.4 provides a description of the methodology used for validating the data.

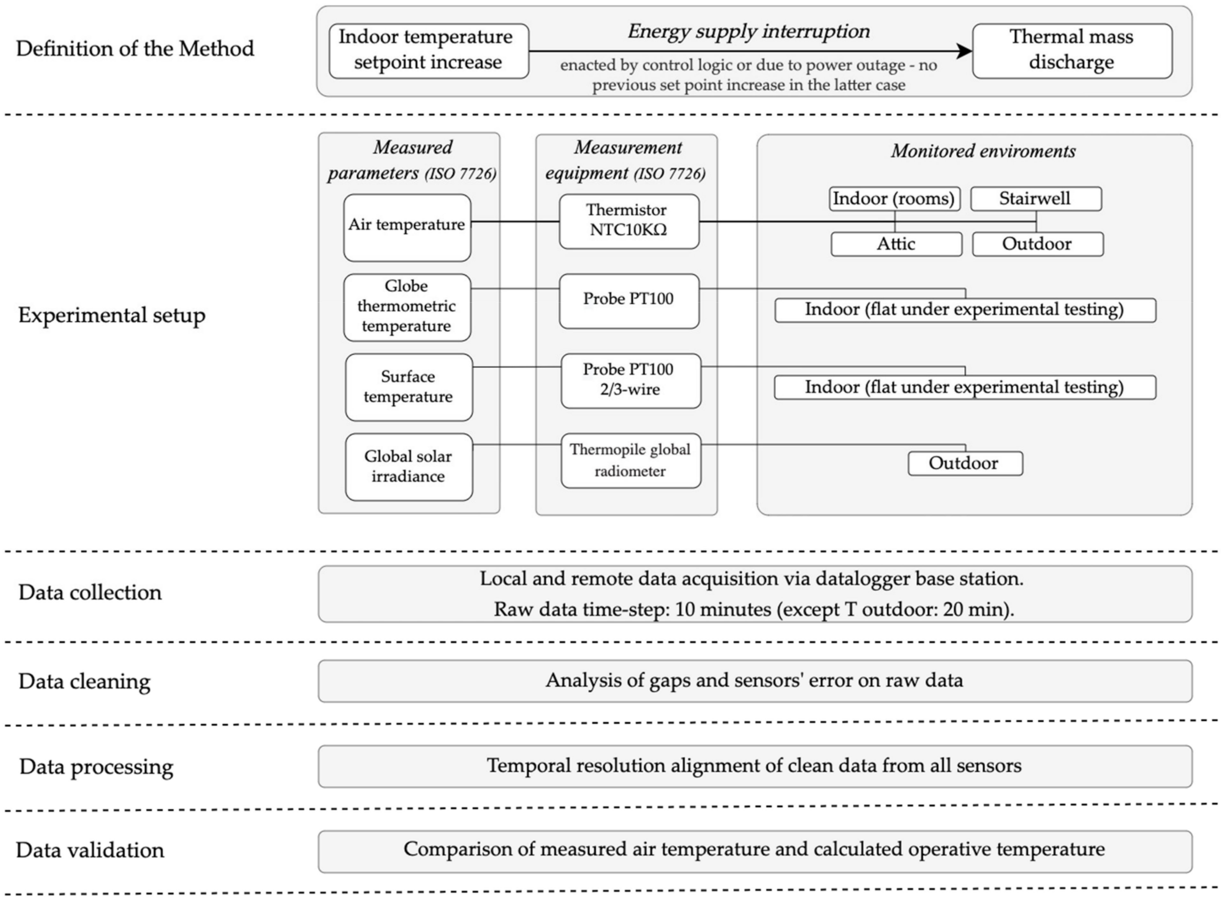

Figure 3. Methodology of data collection and data processing—Extract from [25].

3.1. Methodology

3.1.1. Database 1: Experimental Data (Single Apartment)

The methodology used for the flexibility experiments carried out using the unoccupied apartment can be summarized with two phases:

1. *Charging phase*: Charging of the thermal mass of the unoccupied flat by increasing the indoor air temperature using direct electric resistance heaters which can be operated remotely, both for turning them on or off and for selecting a temperature set point. Additional fans were used to ensure air temperature uniformity across the apartment. The air temperature evolution is measured and recorded.
2. *Discharging phase*: The electric resistance heaters are turned off, and the evolution of the indoor air temperature is recorded, in parallel to measurements of surface temperature, temperatures of adjacent spaces, outdoor conditions, etc. The time interval during which the apartment remains within the comfort range (according to ISO 16798 [27])

and in conditions of thermal safety (according to ASHRAE transactions—2016 [28]) is evaluated.

The activation of the heating system was performed remotely, and subsequently, the temperature setpoint was maintained automatically via an air temperature sensor placed in the center of the apartment and far from the convective air flow generated by the air heaters. During all experiments, the flat remained always unoccupied, the windows' solar protections were kept halfway, and air temperature sensors were equipped with screens to avoid the influence of direct solar radiation.

3.1.2. Database 2: Field Data (Whole Building)

Indoor conditions (air temperature, CO_2, Relative Humidity) were continuously monitored in all the apartments (in one point for smaller apartments, in two points for larger ones). Two unplanned interruptions in the heat delivery from the central heating system, each lasting several days, offered the unforeseen opportunity to document the thermal behavior of the building under such conditions.

3.2. Measured Parameters and Measurement Equipment

3.2.1. Database 1: Experimental Data (Single Apartment)

Figure 4 shows the 3D model of the apartment and the layout of the monitoring system, which consists of sensors for air temperature, globe temperature, and surface temperature.

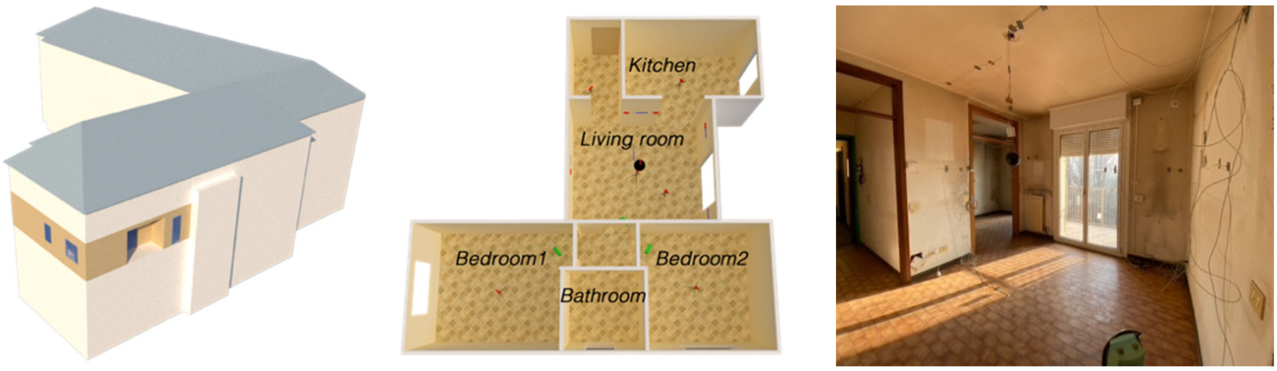

Figure 4. Overview of the test apartment (3D view of the whole building and internal views of the selected apartment).

In addition, sensors measuring air temperature were placed in the apartments adjacent to the flats under study, in the staircase, and outdoors to track the variation in temperature in the boundary environments. Figure 5 includes the plan of the apartment with the localization of all the sensors installed in the flat and in the adjacent spaces. The abbreviations reported in the figure coincide with the names of the variables in the Excel spreadsheet. Figure 6 shows the equipment installed in the test apartment and specifies the heights considered for measuring the different quantities.

Data were acquired using the following sensors:

- Indoor air temperature: Thermistor NTC 10 kΩ (accuracy: ±0.2 °C, resolution: 0.01 °C);
- Surface temperature: PT100 probe (accuracy: ±0.1 °C, resolution: 0.01 °C);
- Globe temperature: PT100 probe (accuracy: ±0.15 °C, resolution: 0.01 °C), black globe (total emissivity: 0.95; diameter: 15 cm);
- Outdoor air temperature, at the building site: Thermistor NTC 10 kΩ (accuracy: ±0.2 °C, resolution: 0.01 °C);
- Horizontal global solar irradiance at a weather station, 6 km away: Pyranometer (thermopile) (accuracy: ±1 W/m^2, max value: 2000 W/m^2);
- Indoor relative humidity: CMOSens technology (accuracy: ±2%, resolution: 0.05%);

- Outdoor relative humidity: capacitive sensor (accuracy: ±1%, resolution: 0.1%).

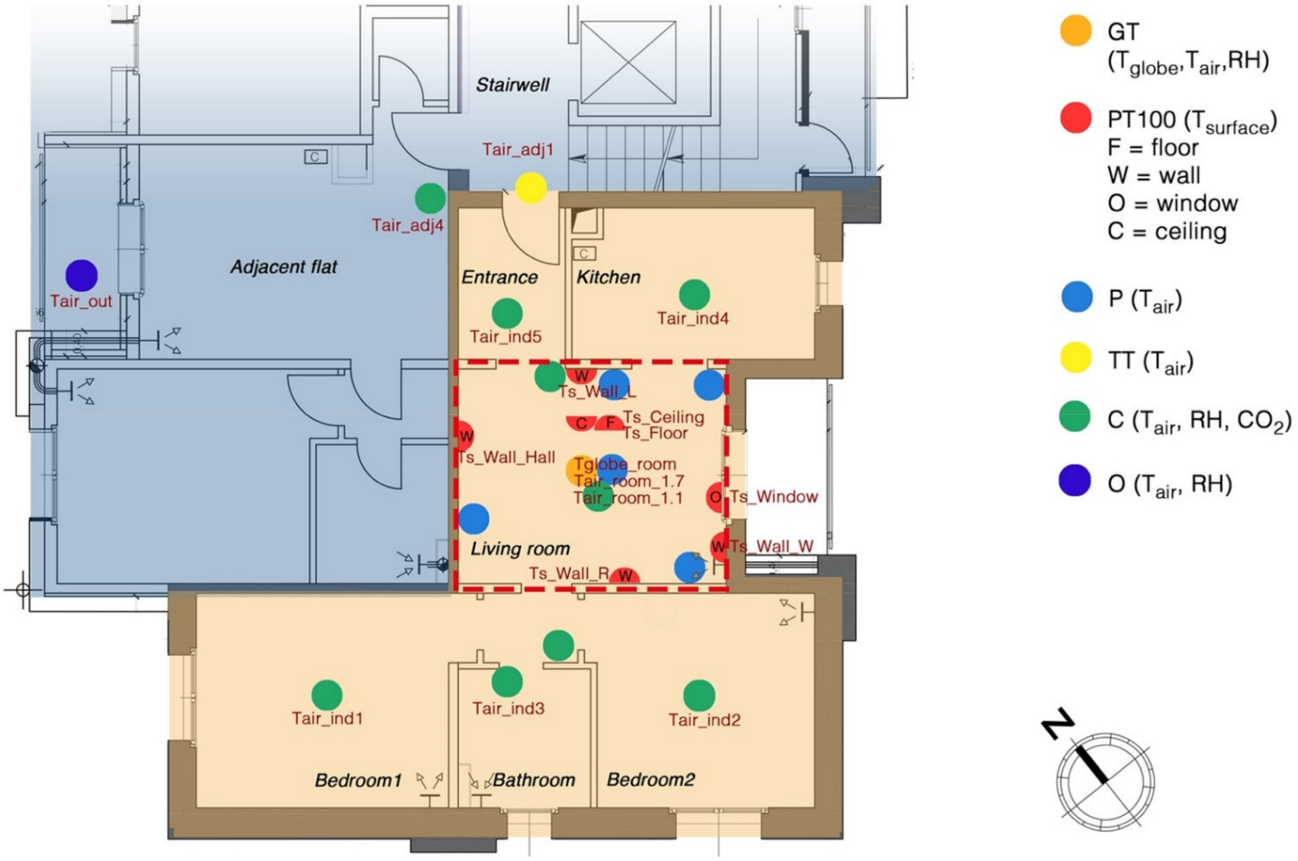

Figure 5. Plan of the test apartment and adjacent zones with the position of all sensors and the names of the corresponding measured variables.

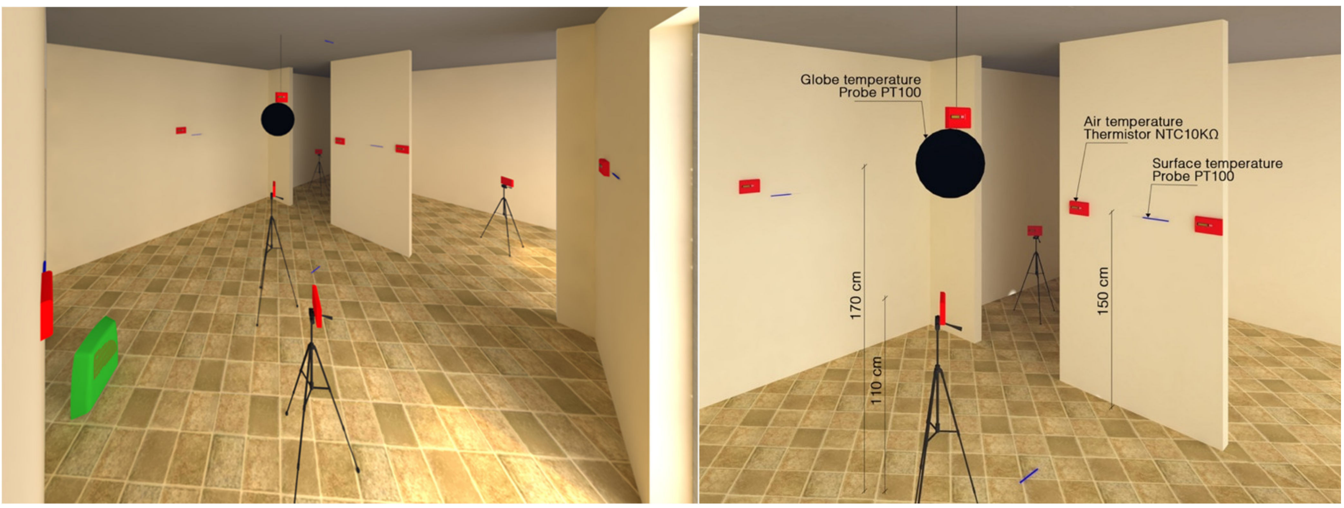

Figure 6. Sensors' setting—indoor overview with installed equipment highlighted (red—air temperature; blue—surface temperature; black—globe temperature; green—electric fan).

All instruments satisfied or exceeded the more stringent requirements of accuracy proposed in the Standard EN ISO 7726:2001—Ergonomics of the thermal environment—Instruments for measuring physical quantities [29]. All measurements were performed with a time-step of 10 min, except for the outdoor temperature, which was measured every 20 min.

The indoor and outdoor air temperatures and surface temperatures were measured by sensors coupled with dataloggers (Capetti WSD00TH2CO, WSD10MiGG and WSD02-TT1K respectively) able to communicate via radio waves with the base-station (Capetti MWDG-MB) located in a technical room at the ground floor of the building. The wireless datalogger gateways were equipped with a serial communication port with MODBUS protocol to export measures. The correspondence between the sampled measures and MODBUS channels is programmable using the WineCapManager software (version 4.1.0, released by Capetti Elettronica s.r.l., Turin, Italy). Figure 7 shows the configuration of the monitoring system.

Figure 7. Configuration levels of the monitoring system for indoor and outdoor air temperatures and surface temperatures.

Globe temperature values were locally collected by means of Tinytag Explorer Data Logging Software (version 6.0, released by Gemini Data Loggers UK Ltd, Chichester, UK). The independent data measurements were synchronized to the 10 min time step when starting each separate measurement stream.

Horizontal global irradiance data were extracted from the ARPA Lombardia Database, a free database released by Regione Lombardia (weather station: Milano v.Juvara). The solarimeter measures radiation values within 300 and 3000 nm with a visibility of 2π steradians. The global radiometer is a thermopile whose external surface has been darkened with matt black paint, having a total reflectivity lower than 2% in the spectral area of the sensor. The global radiometer complies with the standard ISO9060 [30].

3.2.2. Database 2: Field Data (Whole Building)

The field database contains values of global horizontal solar irradiance, outdoor air temperature, and indoor air temperature in one or two points in each apartment. Figure 8 shows the layout of the monitoring system, in a typical floor, for all the apartments of the residential housing complex.

Figure 8. Indoor air temperature sensors distribution in a typical floor of the residential housing complex.

Data were acquired using the following sensors:

- Indoor air temperature: Thermistor NTC 10 kΩ (accuracy: ±0.2 °C, resolution: 0.01 °C);
- Outdoor air temperature: Thermistor NTC 10 kΩ (accuracy: ±0.2 °C, resolution: 0.01 °C);
- Horizontal global solar irradiance: Pyranometer (thermopile) (accuracy: ±1 W/m^2, max value: 2000 W/m^2).

The data logging and data communication system used for this database is the same as the one used for the experimental database (dataloggers: Capetti WSD00TH2CO, WSD10MiGG and basestation: Capetti MWDG-MB), described in detail in the previous section.

3.3. Data Cleaning and Processing

The raw data were exported in the form of CSV or XML files from cloud storage or, in case of local storage, directly from the physical data logger via the dedicated software. Data have been processed to exclude those series which presented gaps due to temporary malfunctioning of the datalogging chain and were aligned as per the time steps, when including one or more data streams in a common Excel/XML. The experimental data were aligned and processed according to a timestep of 10 min and the field data according to a time step of one hour.

3.4. Data Validation

A comparison between operative temperature and air temperature was performed to verify that, thanks to the well-insulated envelope, the air temperature can be considered sufficiently representative of the operative temperature of the indoor environment for use in comfort assessment (data validation phase as in Figure 3). In particular, at the center of the living room of the apartment, at 1.7 m height, the following three quantities were compared: the operative temperature $T_{op,g}$, calculated considering the mean radiant temperature obtained through the use of the globe thermometer; the operative temperature $T_{op,s}$, calculated using the mean radiant temperature calculated from measured values of the temperature of the internal surfaces of the surrounding walls, their area, and their view factor between the chosen position in the room and the surfaces; and the measured air temperature T_a. The absolute difference between operative temperature and air temperature was calculated as $|\Delta T| = |T_{op} - T_a|$, and the median value resulted in the order of 0.11 °C for both procedures, to be compared with a measurement accuracy on air temperature of ±0.2 °C. More details of this analysis phase are presented in the paper by Erba et al. [25].

4. Graphical Representation of Some of the Data Contained in the Dataset

We present here a few graphical representations of part of the data. Figure 9 represents the evolution over time of air temperature approximately at the center of the living room (living room air temperature at 1.7 m above the floor, Tair_room_1.7—column B) during one of the charge/discharge tests.

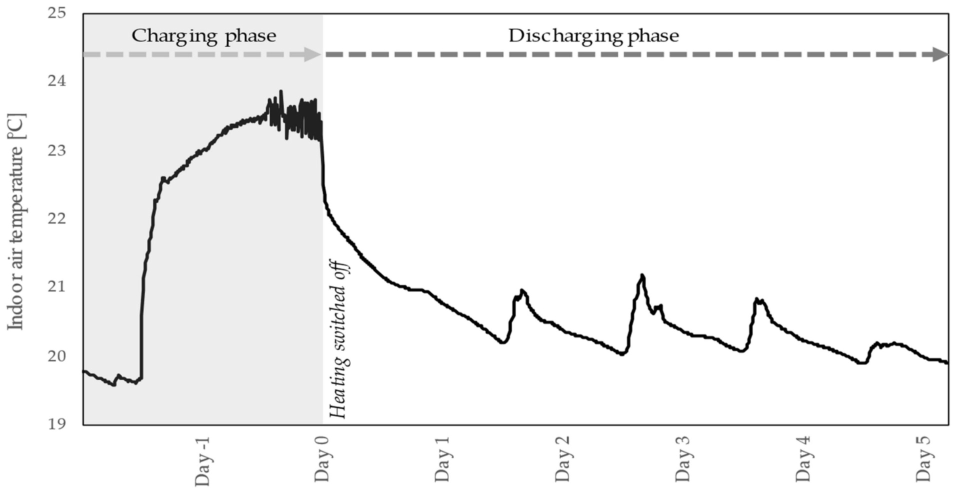

Figure 9. An example of the result of a flexibility test. Tair room 1.7 versus time during one of the tests.

Figure 10 shows the air temperature of all the zones of the flat under experimental testing. The rooms' air temperatures reported in the legend are bedroom1, bedroom2, bathroom, kitchen, entrance, and living room.

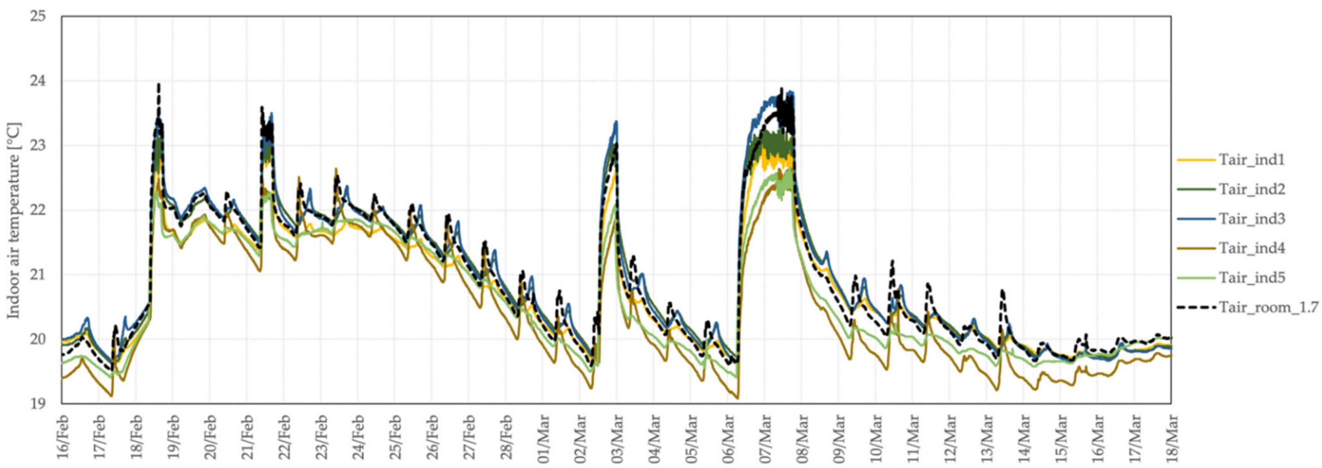

Figure 10. Air temperatures in all the rooms of the test apartment.

Figure 11 represents the thermal behavior of a number of apartments belonging to the two building blocks during the winter heating power outage from 7 to 12 January 2022.

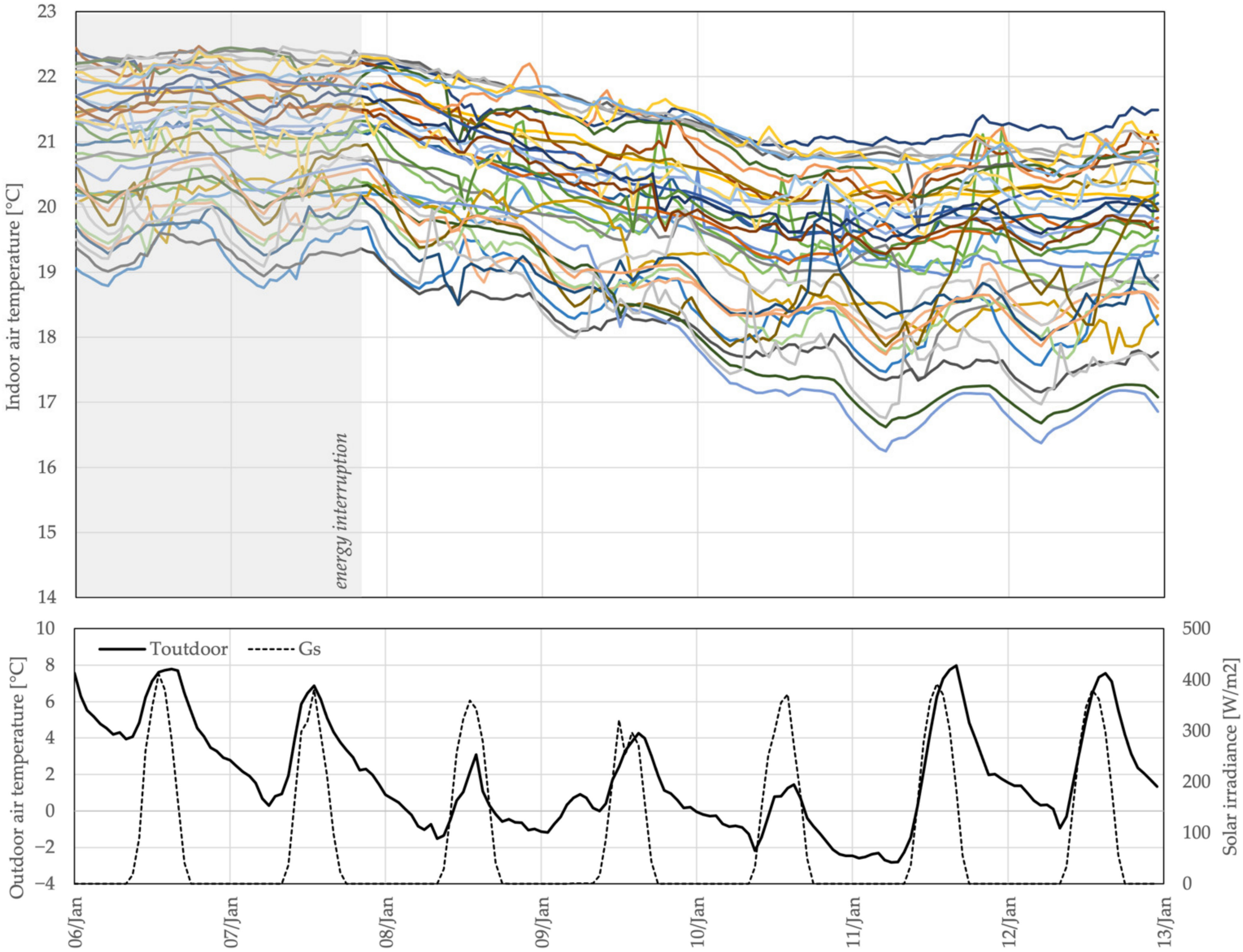

Figure 11. Upper part: Measured indoor air temperature in various apartments of the building during the January power outage (7 to 12 January 2022). Lower part: outdoor air temperature and global horizontal solar irradiance during the same days.

Table 2 shows the start and end of all tests reported in the database "Experimental data_Flexibility tests_Flat level" and the external conditions (i.e., average, minimum, and maximum temperature) during the load-shifting phase (i.e., phase during which the heating system is kept off).

Table 2. Overview of tests reported in database "Experimental Data_Test apartment_Flexibility tests".

ID Test	Charge	Load-Shifting		
	Date Start [dd/mm hh:mm]	Date Start [dd/mm hh:mm]	Date Stop [dd/mm hh:mm]	$T_{out\ Avg\ (min;\ max)}$ [°C]
F2_22_2	16/01 00:50	18/01 09:20	20/01 15:00	5.2 (0.5; 11.4)
F2_22_3	20/01 15:10	21/01 12:10	25/01 03:10	2.2 (−2.7; 6.9)
F2_22_4	26/01 08:40	28/01 08:40	30/01 08:40	5.9 (−0.6; 15.7)
F2_22_5	30/01 08:50	03/02 17:30	12/02 07:20	7.8 (0.6; 15)
F2_22_6	12/02 07:40	14/02 16:00	16/02 16:00	3.7 (0.5; 9)
F2_22_7	17/02 17:30	18/02 17:30	21/02 08:40	9.5 (5.4; 15.2)
F2_22_8	21/02 09:40	21/02 16:50	02/03 09:00	8.8 (−0.3; 19)
F2_22_9	02/03 09:10	03/03 00:20	05/03 19:20	8.5 (4.1; 15.1)
F2_22_10	05/03 19:30	07/03 19:10	20/03 10:30	9.1 (−1; 16.5)
F2_22_11	29/03 10:20	30/03 17:50	10/04 13:40	11.9 (3.9; 24)

5. Conclusions

The paper describes the measured data and the methods of data collection and processing related to the study developed in a multiapartment housing block located in Milan, Italy, which has recently undergone a deep energy retrofit and has been used as a thermal battery during the winter season. Two datasets are provided: the first one refers to the measurements conducted in one unoccupied flat of the building complex, in which the authors have carried out a series of experimental tests under controlled conditions; the second one reports the measurements of the indoor air temperature in several apartments of the housing block during two real cases of power outage that lasted several days each. In both cases, the data show the ability of the buildings with significantly improved thermal envelope quality, to maintain indoor conditions within the comfort range and/or providing thermal safety for several days.

Given the growing frequency and risk of extreme weather events which may impact on energy supply, from generation to transmission and distribution, and the plans for accelerated growth of the share of intermittent renewables, the measured data presented can be useful for academics, engineers and energy modelers to study demand-side flexibility strategies to cope with the above challenges. Energy flexibility services may be developed to support managers of building portfolios, energy companies, or system operators engaged in delivering stable energy system operation.

Author Contributions: Conceptualization, S.E.; methodology, S.E.; investigation, S.E. and A.B.; data curation, S.E. and A.B.; formal analysis, S.E. and A.B.; writing—original draft preparation, S.E.; writing—review and editing, S.E. and A.B.; visualization, S.E. and A.B.; funding acquisition, S.E. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in this study are openly available in Mendeley Data at DOI: https://doi.org/10.17632/b63c2gtynh.1.

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

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