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Indoor monitoring and long-term survey to identify the risks of Energy Poverty: the case of social housing in Northern Italy

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Abstract. Low-income families often live in poorly heated houses belonging to social housing programs. Tenants' wellbeing and health in social housing is typically threatened by problems associated with energy inefficiency and poor Indoor Environmental Quality (IEQ). These conditions are among the symptoms of a social issue known as Energy Poverty (EP), which occurs when residents face difficulty in paying energy bills. In 2020 about 2.1 million households (8% of the total) were suffering from energy poverty in Italy. The risk of EP is mainly favored by three factors: the low income of the family, the high final price of energy and the poor technical construction characteristics of the building which can lead to poor IEQ. Four indicators have been proposed by the European Commission and some others developed in the scientific literature, but often neither the thresholds to assess the status of EP nor the methodology to collect data have been defined. This study aims to assess some of the recommended European indicators on a case study. The risks of EP have been investigated in social housing located in Northern Italy by means of an integrated methodology based on a site inspection, a survey, and the continuous monitoring of the indoor environmental parameters during the winter season. The proposed method allowed detecting the presence of EP in 5 dwellings out of 8.

1. Introduction

Energy Poverty (EP) occurs when households are incapable to get access to essential energy services. According to the Energy Poverty Advisory Hub (EPAH) [1], EP is a combination of contextual factors (i.e, geographical location, dwelling type, heating/cooling systems and geopolitical aspects influencing the energy prices) and personal vulnerability factors, such as low level of education, single parenting, families with disabilities or pensioners, and it is favored by three factors: the low income of the family, the high final price of energy and the poor technical quality of the building. Families in EP condition spend a very high share of income for energy or face difficulty in paying energy bills (i.e., electricity, fuel, and heating) [2-3]. In 2018 nearly 34 million Europeans were unable to afford to keep their homes "adequately warm" [4]. In Italy, low-income families can access to low-rent houses within social housing programs. In 2023 the Italian public housing covers 2.2 million inhabitants living in 836 thousand houses managed by 74 local authorities and associated companies [5]. Often these houses have a low energy performance, leading tenants to vulnerable conditions.

Despite EP is generated by economic causes, it may have repercussions on other not income-related aspects, such as tenants' well-being and health. Although during the last decades the problem of EP has been framed, it is not easy to be assessed and tackled due to its complexity. According to EU

Recommendation 1563/2020 [4] the EP assessment can be carried out by means of different kinds of indicators: economic indicators comparing the energy expenses with income; indicators based on self-assessment when households are asked directly to what extent they feel able to keep the house warm; indicators based on direct measurement of physical variables to determine the adequacy of energy services (e.g. room temperature); and indirect indicators such as utility bills paid in delay or poor housing quality. Based on the EU Recommendation, scientific literature proposes and discusses several EP indicators [6-9]. Three main different approaches to detect EP could be identified [7-8], namely (i) the direct approach, such as the measurements of the indoor temperature "when looking for households unable to guarantee an adequate indoor thermal regime"; (ii) the income/expenses approach, such as the Boardman's 10% metric which indicates households whose fuel expenditure exceeds 10% of the income, or the Low Income High Cost metric (LIHC) which aims to measure both the level and depth of energy poverty; and (iii) a subjective approach, i.e., the household's living condition self-assessment, which is mainly implemented using the European union survey on income and living conditions (EU-SILC) [10] indicators, i.e., the "inability to keep homes adequately warm during winter", the "delay in the payments of utility bills" or the "presence of deficiencies in the dwelling" [8] such as the presence of mould, low temperatures, insufficient ventilation, or rot in windows frames. Furthermore, [9] also include thermal aspects analyzing the hours when households' temperature is out of the comfort ranges. Unfortunately, except for the economic indicators, a quantitative definition of all the other indicators, neither the threshold values nor the modality to collect direct indicators are defined by the EU Recommendation; moreover a shared set of indicators cannot be found in the literature. So, the aim of this study is to assess self-reported, indirect and direct indicators recommended by the European Commission on a case study. In particular, their explanatory capacity was tested on a sample of dwellings occupied by families likely to be affected by EP, as it could be argued by the fact that their houses are rented to low-income tenants. This required developing a dedicated methodology to collect and analyze data. Moreover, some reference thresholds to associate quantitative measurements to EP conditions, for a given IEQ condition, were established (i.e. 50 % of discomfort time). To this aim, the reference values in the European Standards ISO 7730 [11] and EN 16798 [12] for the Indoor environmental quality assessment were considered, on the basis that discomfort was related to EP. The EP indicators assessment was carried out through an integrated approach that includes (i) a survey, (ii) a site inspection and (iii) a monitoring campaign. The survey allowed to inspect tenants' social-cultural and behavioral aspects linked to vulnerable conditions, and to collect the self-reported perceived IEQ conditions to be compared with the objective indoor measurements. The site inspection was carried out to assess the quality of the houses and in particular the presence of some EP symptoms indicated by the EU Recommendation [10], such as damp walls and mould on thermal bridges and rot in windows frames. The IEQ monitoring allowed to measure the indoor conditions determined by the system and the building operation (i.e., air temperature, humidity and CO_2 concentration). Despite in the literature only room temperature is mentioned as a direct EP indicator, in this work also air humidity and CO_2 were measured as indirect objective indicators of EP. In fact, high air humidity and CO_2 concentration is expected to be a consequence of a limited ventilation, which is indicating the need of limiting ventilation loads, saving energy and, consequently, costs.

2. Data and Methods

This research consists in a field campaign carried out in 8 apartments located in three social housing buildings (Fig.1) in Belluno (Lat. 46°9'1"08 N), during the winter season 2023 for a continuous period (10th February -15th March 2023). The campaign includes the collection of subjective data (i.e., tenants' survey) and objective data (i.e., site inspection of households' quality and measurements of IEQ parameters) in order to (i) investigate the EP risk factors and (ii) measure the EP symptoms, respectively.

2.1. Investigation of EP risk factors by means of tenants' survey

A survey was designed to capture families' personal vulnerability and their behavior in managing the house and the heating system.

Figure 1. Case studies: main façade of the three monitored social housing buildings in Belluno.

Moreover, tenants' perception of IEQ was asked. In particular the survey aims to highlight the following EP risk factors:

- social and cultural factors: people with low levels of education, immigrants, single parenting, pensioners, families with disable people;
- factors regarding tenants' behavior about house management: set-point temperature lower than 20 °C, the number of heating hours lower than 6 hours (which one fourth of the allowed heating time according to the Italian law for the climatic zone F), presence of unheated rooms, windows opening time less than 1h a day;
- self-reported assessment of IEQ conditions about air temperature, air humidity and indoor air quality.

The survey was carried out by means of a long-term questionnaire which is divided into 6 parts: (i) General information (i.e., country of origin, number of inhabitants, age, gender, education degree, type of employment); (ii) Household's management (i.e., occupancy, windows and shadings operation, use of artificial lighting and type of lamps, use of home appliances; (iii) Heating system description and management (i.e., type of generator, fuel and terminals, thermostat and setpoint, system operating schedule); (iv) Self-reported indoor conditions regarding thermal, IAQ, acoustic and visual domains; (v) General satisfaction and Sick Building Syndrome symptoms; (vi) Actions for facing discomfort and energy saving.

2.2. Investigation and measurement of EP symptoms: site inspection and IEQ monitoring

The site inspection consists in a checklist for collecting information concerning the maintenance conditions of the apartment, such as the presence of mould, damp walls or rot in window frames which are commonly considered EP symptoms [8]. The monitoring campaign consisted in continuous measurements of environmental parameters. The indoor temperature, relative humidity and carbon dioxide concentration were monitored at 5 minutes intervals through 16 data loggers located in 8 apartments. Two sensors have been installed in each unit, to monitor the IEQ parameters in the living area and in the main bedroom. The characteristics and specifications of the sensors are reported in Table 1. The collected dataset was used to calculate the Discomfort time, i.e., the percentage of time when temperature, relative humidity and CO_2 do not fulfil the comfort thresholds suggested by ISO 7730 [11] and EN 16798 [12]. According to the international standards EN ISO 7730:2006 and EN 16798-1: 2019 [11-12] the comfort ranges of category II has been considered to assess the indoor environmental quality, that means a range of air temperatures between 20 °C and 24 °C, an interval of relative humidity between 25 % and 60 %, while the considered acceptable values of CO_2 concentrations were up to 800 ppm and 550 ppm above outdoors (i.e., 400 ppm), respectively for living rooms and bedrooms.

Table 1. Long-term monitoring: specifications of instruments and physical parameters measured.

No.	Instrument	Parameters	Specification
1	HOBO® MX1102A	CO_2 Ambient Temperature (T) Relative Humidity (RH)	CO_2: Range: 0 ÷ 5000ppm; Accuracy ±50ppm; T: Range: 0°C ÷ +50°C; Accuracy: ± 0.2°C RH: Range: 1% ÷ 90%; Accuracy ±2%
2	Aranet4	CO_2 Ambient Temperature (T) Relative Humidity (RH)	CO_2: Range: 1 ÷ 9999ppm; Accuracy ±30 ppm; T: Range: 0°C ÷ +50°C; Accuracy: ± 0.3°C RH: Range: 1% ÷ 85%; Accuracy ±3%

3. Results and discussion

3.1. EP risk factors
Looking at the social cultural aspects and the behavior of the families in the household management, it can be seen that the eight surveyed families present from 3 to 6 EP risk factors. Table 2 reports for each family the occurring factors. The number of the families' members has been reported in order to highlight the situations of copious families (i.e., parents with many children) that is the case of unit A8. In the majority of cases houses are inhabited by pensioners. According to this first screening families living in A1, A2, A3, A7 and A8 declare that they switch the heating on less than 6 hours a day, so they could run the risk of inadequate thermal environment.

Table 2. EP risk social and cultural factors, and behavioral risk factors. The cross highlights the factor occurrence in each unit.

	Unit	**A1**	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**
	Number of tenants	1	2	2	1	4	1	2	7
Social/cultural risk factors	Single parenting			X				X	
	Pensioners	X	X	X	X		X		
	Disability			X	X		X		
	Low-level education (< Grade 8)	X	X	X	X	X	X	X	
	Immigrants								X
Behavioral risk factors	Heating system ON < 6h	X	X	X				X	X
	Set point < 20°			X					X
	Unheated rooms		X			X			
	Window open < 1 h a day	X	X		X	X	X		

3.2. EP symptoms measured by site inspection and monitoring
Figure 2 shows the indoor conditions of each monitored apartment by means of boxplots representing the percentage distributions of indoor temperature, relative humidity and CO_2 concentration measured in the living rooms and bedrooms. The extreme values represent the maximum and the minimum, the cross is the average value, while the line inside the box is the median value. Each box is delimited by the 25th and 75th percentile. During the monitored period the temperature inside all the households goes down the comfort lower limit of 20°C at least for 50 % and 75 % of the time, respectively in the living rooms and in bedrooms, except for apartment A4 where temperatures are inside the comfort range for almost all the time sometimes even exceeding 24 °C. The relative humidity exceeds the upper limit of 60 % only in household A8, where temperatures are even below 16 °C for almost all the time. Low temperature and high humidity could represent a warning light of energy poverty. Site inspection also revealed damp walls and mould in this apartment. Mould on the walls was noticed also in A7. Regarding the IAQ, except for household A1, A2, A4 and A6, CO_2 concentration in the living room always exceeds the limit of 1200 ppm, while the in the bedrooms is always higher than the threshold, with the worsen conditions in A7 and A8 where the CO_2 exceeds 4000 ppm. From these results units A1, A5 and A8 could be occupied by families in EP condition.

3.3. Comparison between objective and self-reported conditions assessment
According to the Recommendation EU 2020/1563 [4] and other authors [6-9] the measured room temperature and the self-reported condition provided by people can be used as indicators of energy poverty, however, no common threshold for the indicators has been found yet. In this work the percentages of discomfort time have been used and discomfort conditions for more than 50 % of the time have been considered as symptoms of EP. Table 3 and 4 summarize respectively the results of the objective and self-reported indoor assessment. According to this threshold it can be noted that units A1, A2, A5, A7 and A8 present inadequate thermal conditions both in the living room and in the bedroom;

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while A3 and A6 have inadequate temperature only in the bedroom. Looking at the self-reported perception, however, only tenants of A1 and A6 reported that the house is cold (Table 4).
Regarding the humidity, only unit A8 exceeds the threshold, reporting more than 60 % of RH for almost 80% of the time in the living room and for the 90 % of the time in the bedroom. Unfortunately, the tenant rejected the survey. High humidity was claimed by tenants of A2 and A3 but in those units the threshold was never exceeded.

As concerns the IAQ, the percentage of discomfort time is higher than 50 % in units A3, A7, A8 both in the living room and bedrooms, while in units A1 and A5 the CO_2 level exceeds the threshold for more than the 50 % of the time only in the bedroom. Regarding the IAQ subjective assessment only the tenant of A7 answered coherently with the measurement, while all the others did not.
The comparison between objective and self-reported conditions assessment demonstrates the little reliability of the subjective assessment: people does not comply for the poor indoor quality even when the indoor conditions are widely under the comfort limit for all the time.

Figure 2. Boxplots of indoor temperature, relative humidity and CO_2 concentration distribution in living rooms and bedrooms. The red lines indicate the comfort thresholds.

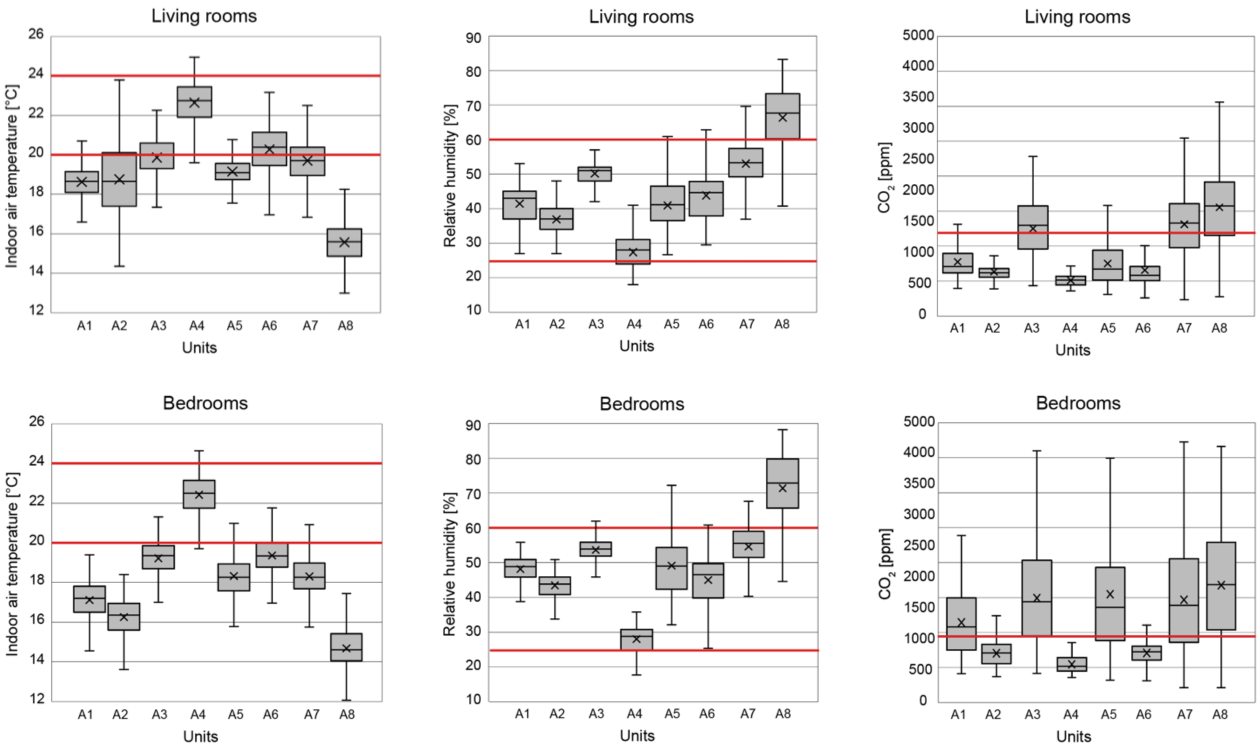

Table 3. Objective indicators: percentage of discomfort time in the monitored units (L=living room, B=bedrooms). Grey shades indicate discomfort time >50%.

Unit	A1		A2		A3		A4		A5		A6		A7		A8	
	L	B	L	B	L	B	L	B	L	B	L	B	L	B	L	B
%DT<20°C	99	100	73	100	49	81	1	2	90	95	39	75	63	94	100	100
%DT>60%	0	0	0	0	0	2	0	0	0	1	1	1	14	18	77	90
%DT>800 ppm	14	-	2	-	68	-	0	-	15	-	6	-	71	-	79	-
%DT>550 ppm	-	67	-	20	-	79	-	0	-	76	-	15	-	73	-	79

Table 4. Self-reported indoor conditions

Unit	A1	A2	A3	A4	A5	A6	A7	A8
COLD house	X					X		N/A
HUMID house		X	X					N/A
STUFFY air		X				X	X	N/A

4. Conclusions

This paper proposes an integrated approach for detecting the risks and the symptoms of energy poverty in 8 social housing apartments by means of both in-field monitoring and tenants' survey. According to the survey, all the households reveal the presence of at least 6 EP risk factors out the 9 analyzed. The vulnerability condition is then confirmed in at least 5 out 8 apartments (A1, A2, A5, A7, A8).
Going beyond the studied case, some general conclusions regarding the assessed EP indicators, , can be reported:

1. A set of common and standardized thresholds for the direct indicators, such as the minimum room temperature and the percentage of time for a room temperature below that minimum, is needed.
2. Self-reported indicators may not be reliable when assessing EP.
3. Indoor monitoring of air temperature, humidity and CO_2 concentration is effective in highlighting the EP condition.

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