How the COVID Pandemic and the Energy Crisis Have Influenced Indoor Environmental Conditions in non-residential Buildings

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ABSTRACT

Building energy behaviour and indoor environmental conditions have been changing due to different external events that have been taking place at global level from 2020, from the COVID pandemic (2020-2022) to the energy crisis (mainly from the war in Ukraine from February 2022). During these events, existing naturally ventilated (NV) buildings have had to balance minimum thermal comfort, high levels of ventilation (to reduce CO_2 concentration and risk of infection) and the lowest energy costs. Museums and schools are examples of non-residential buildings with different but high specific requirements of thermal comfort and Indoor Air Quality (IAQ). In the case of educational buildings, these requirements are demanding, since the users are children and adolescents who need to concentrate for learning and wellbeing. Schools are occupied during specific class schedules and with high levels of occupancy in the classrooms. On the other hand, demanding requirements are also characteristic of museums, which must ensure adequate indoor environmental conditions for the conservation of collections, all year during all hours of the day, but with low levels of occupancy.

This study presents three case studies, two high schools and a museum, in a location with a temperate climate in the North of Spain. They are NV buildings with low levels of energy performance, working with oil boilers without adequate control and regulation of the heating system. The analysis is based on heating energy consumption and monitoring data from 2019 (previous to the COVID pandemic), during 2020/2021 and 2021-22 (during COVID pandemic) and until 2023 (without any COVID restrictions and during an energy crisis). In addition, the study includes the analysis of questionnaires to the staff (directors and secretaries, and maintenance personnel) and managers (from the public regional administration), regarding their switch of their environmental perceptions and priorities from prior COVID to post COVID and energy crisis. In addition, some answers about their preferences in relation to the energy retrofit priorities for the buildings they have in charge were collected.

School data shows how high level of CO_2 concentration prior to the pandemic, are followed by two years of low and adequate levels for a NV buildings during COVID (mean values of 1000ppm). However, after the pandemic, CO_2 concentration levels have risen due to the new concerns for energy costs in the two case studies (to mean values of 1500ppm). In all case studies, indoor temperatures have been balanced during COVID to a minimum but with a high energy consumption (up to 30%); and finally in 2022-23, consumption has decreased a 10% since before COVID consequently worsening IAQ. The study of existing NV buildings dealing with external events, helps understanding the potential and benefits of NV. Lessons learned should be considered in the upgrade of existing buildings.

KEYWORDS

Thermal comfort, monitoring, surveys, naturally ventilated, energy consumption

1 INTRODUCTION

Existing naturally ventilated (NV) non-residential buildings have to ensure adequate Indoor Environmental Quality (IEQ) with low energy costs and without mechanical ventilation (MV). In locations with cold winters and during the external events that have affected worldwide since 2020 (COVID pandemic and energy crisis), balance thermal comfort and adequate Indoor Air Quality (IAQ) has been a challenge only possible with a high compromise of staff and/or occupants.

Monitoring systems suppose a useful tool to control the efficiency of the manual actions in these NV buildings, even low costs systems and/or covering only selected spaces of the building, to understand their global performance (Monge-Barrio et al., 2022). Schools and other public buildings opened even during pandemic in Spain (from September 2020) laying on the promotion of natural ventilation, and in some buildings supported on data of these systems registering temperatures and CO2 concentration.

On 2022 and after the COVID pandemic, have emerged new external events as an energy crisis (affecting increasing energy prices and risk of provisions) that also affects worldwide very directly to NV buildings, that have to manage thermal comfort and IAQ with energy consumption and increasing energy costs.

This study goes throughout these four winters (from 2019-20 to 2022-23) to investigate the shift among different environmental parameters and energy performance, with three Case Studies of non-residential buildings (a museum and two high schools) through the analysis of monitoring data (temperature and CO2 concentration), heating consumption data available of two of the buildings, and surveys to relevant staff in charge.

2 METHODS

2.1 Climate

The study analyses IEQ in three different non-residential buildings located in Pamplona, in the North of Spain, with a temperate climate without a dry season, Cfb ‘‘oceanic” according to Köppen-Geiger classification. Following data from the 1980–2010 climate series of the Spanish State Meteorological Agency, AEMET (see www.aemet.es), mean annual temperature is 12.7 ºC, January being the coldest month of the year, with a monthly mean of 5.2 ºC and a monthly average minimum of 1.4 ºC.

2.2 Case Studies

This study is focused on two typologies of non-residential buildings with high and different requirements on indoor environmental conditions as a museum and a high school. In museums, the main objective for the collection maintenance is primarily focused on the stability of relative humidity (RH), and with some thresholds of minimum and maximum temperature and RH, always maintaining low daily swings (ASHRAE, 2011). In schools, RH swings are not relevant but maintaining adequate temperatures and IAQ within some ranges in relation to Categories of buildings. However, existing buildings naturally ventilated (without mechanical ventilation, NV, and without Air Conditioning, AC) and with heating systems, present a challenge to maintain adequate environmental conditions according to their use. While the buildings are not upgraded and during external events that have affected worldwide IEQ and consumption in buildings, they have to balance manually thermal comfort, IAQ and energy consumption. This study analysed data and surveys of three buildings (Fig.1) that are briefly described below.

The museum of Navarra (MN) is the main public museum in the Community of Navarra, with collections from the antiquity to nowadays. The Museum of Navarre has been located in an old Hospital of sixteenth century since 1956, after two main rehabilitations in that year and later in 1990. The building has a longest wing dedicated to exhibitions, with south-west and northeast orientations without any shading, and a shortest wing with office spaces. The ground floor incorporates an old chapel (as an exhibition hall), an Auditorium, and different rooms for temporary and permanent exhibitions, and a basement under a courtyard with a large central skylight that also accommodate permanent collection.

MN building has a heating system with two diesel boilers, with manual regulation according to use and climate, and with temperature sensors per circuit, and with radiator. Only the total annual and quarterly consumption of diesel is available. The museum has portable humidifiers and dehumidifiers in some rooms to control manually RH. Only photo library in the basement, some offices in the administration area, children’s workshops, and the Auditorium, have some punctual AC systems, but those rooms are not studied in this analysis (Monge-Barrio et al., 2021).

High School IES.NV (from its acronym in Spanish) was built in 1971 with a spinal typology of building, being classrooms mainly facing South-West. Only windows have been renovated during the last 10 years. The building also has an oil boiler and radiators, and the system is only regulated by on/off with a schedule per circuit (6 circuits, one per each main wing of 9 classrooms), and there are no thermostatic valves on the radiators. Heating consumption is collected manually and monthly by the staff.

High School IES.PC (from its acronym in Spanish) was built in 1944 with a squared-shaped and courtyard typology of building. Some windows are not yet upgraded, and even some of them are fixed. Unfortunately, there is not available specific heating consumption data in this school, what suppose a usual barrier to improve and optimize energy performance in existing buildings.

Figure 1: Non-residential Case Studies: Museum of Navarra, IES.NV and IES.PC High Schools

2.3 Monitoring and data consumption

In these buildings, having a monitoring system have supposed an important tool in which lean on to balance IEQ during these events. Although installed in different moments and with different parameters, all of them has *Sensonet* sensors connected via radio to a central data logger, displaying 10-min data. Summary of available monitoring data for analysis is shown in Table 1.

Table 1: Summary of available monitoring data in Case Studies

Winter	Situation	IES_NV Monitoring data	IES_PC Monitoring data	MN Monitoring data
2019-20	COVID, schools closed at March15th 2020	3-15/03/20	NA	12/19 – 2/20
2020-21	COVID Schools opened*	12/20 – 2/21	NA	12/20 – 2/21
2021-22	COVID Schools opened*	12/21 – 2/22	12/21 – 2/22	12/21 – 2/22
2022-23	Post Covid & Energy crisis	12/22 – 2/23	12/22 – 2/23	12/22 – 2/23

Notes: *. With natural ventilation as main strategy in schools without VAC

Museo de Navarra building has a monitoring system of temperature and RH in the main rooms (and special showcases), in all floors and different orientations (accuracy ±0,4 °C in temperature and ±3% in RH), being available for this study data from 2019 to 2023. Heating consumption. CO_2 concentration was registered during the winter 2020-21 with mean values lower than 900ppm due to the occupancy rate, therefore this parameter is not considered in this building. A summary of available data per winter is in Table 2.

Table 2: Monitored rooms in Museum of Navarra MN and parameters

Room	Floor/ Orientation	19-20 (Dec to Feb)	20-21 (Dec to Feb)	21-22 (Dec to Feb)	22-23 (Dec to Feb)
"*Prehistory and Roman*"	BM / Skylight	T/HR	T/HR	T/HR	T/HR
Temporary Exhibitions	GF / -	T/HR	T/HR	T/HR	T/HR
"*Middle Ages*"	F1 / -	T/HR	T/HR	T/HR	T/HR
"*Roman*"	F1 / W	T/HR	T/HR	T/HR	T/HR
"*Middle Ages, paintings 1*"	F2 / W	T/HR	T/HR	T/HR	T/HR
"*Middle Ages, paintings 2*"	F2 / N	T/HR	T/HR	T/HR	T/HR
"*Goya*"	F3 / E	T/HR	T/HR	T/HR	T/HR
Room of restoration	F2 / E&S	T/HR	T/HR	T/HR	T/HR
"*20th century, paintings, 1*"	F4 / W	T/HR	T/HR	T/HR	T/HR
"*20th century, paintings, 2*"	F4 / W	T/HR	T/HR	T/HR	T/HR

IES.NV High School has monitored some selected classrooms till winter 2021-22 when a new system with sensors in all classrooms in the building were installed. For the purposes of this study, only the original monitored classrooms selected in different floors, were analyzed to compare (Table 3). Some classrooms on 2020-21 had PMx measures, and some corridors in the following years, although those parameters are not studied for being installed in different spaces. During the first winter pre-COVID, data was registered with low cost mini sensors *Madge Tech* for temperature (accuracy ± 0.5 ºC) and *Extech* Data Loggers for CO_2 concentration (accuracy ± 50 ppm), for not having installed the system in the building yet. Those data in March was studied, for being typical for the winter season in the location (Monge-Barrio et al., 2022).

Table 3: Monitored rooms in IES.NV High School and studied parameters

Room	Floor/ Orientation	Rate Occ. (m3/p)	19-20 (March*)	20-21 (Dec to Feb)	21-22 (Dec to Feb)	22-23 (Dec to Feb)
ESO_1C	GF / S	6,38	T/HR/CO2	T/HR/CO2	T/HR/CO2	T/HR/CO2
ESO_2B	GF / S	6,38	T/HR/CO2	T/HR/CO2	T/HR/CO2	T/HR/CO2
ESO_3A	F1 / S	6,13	T/HR/CO2	T/HR/CO2	T/HR/CO2	T/HR/CO2
ESO_3C	F1 / W	4,80	T/HR	T/HR/CO2	T/HR/CO2	T/HR/CO2
ESO_4C	F1 / S	5,80	T/HR	T/HR/CO2	T/HR/CO2	T/HR/CO2
ESO_4F	F1 / S	5,22	T/HR/CO2	T/HR/CO2	T/HR/CO2	T/HR/CO2
BACH_1D	F1 / W	7,14	T/HR/CO2	T/HR/CO2	T/HR/CO2	T/HR/CO2
BACH_2B	F2 / S	7,19	T/HR/CO2	T/HR/CO2	T/HR/CO2	T/HR/CO2
BACH_2D	F2 / S	6,56	T/HR/CO2	T/HR/CO2	T/HR/CO2	T/HR

Notes: *- March 3-13th 2020 (8 school days) before Spanish COVID lockdown, registering typical outdoor conditions for winter in the location

PC High School has a monitoring system from 2021 during the last year of pandemic and after that. Classrooms were selected in different floors and orientations, mainly facing streets with medium traffic (Table 4). Some of the classrooms have PMx measures, but was not analyzed in this study.

Table 4: Monitored rooms in IES.PC High School and parameters

Room	Floor/ Orientation	Rate Occ. (m3/p)	19-20	20-21 (Dec to Feb)	21-22 (Dec to Feb)	22-23 (Dec to Feb)
ESO_1C	GF / SW&SE	13,18	NA	NA	T/HR/CO2	T/HR/CO2
ESO_1E	GF / SW	15,00	NA	NA	T/HR/CO2	T/HR/CO2
ESO_1F	GF / SE	13,36	NA	NA	T/HR/CO2	T/HR/CO2
ESO_3F	F1 / SW	11,98	NA	NA	T/HR/CO2	T/HR/CO2
ESO_4C	F1 / SE	10,16	NA	NA	T/HR/CO2	T/HR/CO2
BACH_1B	F2 / SW&SE	8,49	NA	NA	T/HR/CO2	T/HR/CO2
BACH_1F	F2 / SW	9,67	NA	NA	T/HR/CO2	T/HR/CO2
BACH_1G	F2 / SW	12,42	NA	NA	T/HR/CO2	T/HR/CO2
BACH_2C	F2 / SE	9,33	NA	NA	T/HR/CO2	T/HR/CO2
BACH_2H	F2 / SW *	9,46	NA	NA	T/HR/CO2	T/HR/CO2

Notes: NA. Not available, because there was not any monitoring system installed; *- All classrooms face streets but BACH_2H that face a courtyard

2.4 Surveys

Some surveys to personnel in charge of the three buildings were conducted on line (through google forms) during May 2023, that is, at the end of the last winter season studied. These surveys were obtained from building staff (directors and secretaries, and maintenance staff) and managers (from the public and regional administration). The questions are related mainly to the change of their perception before COVID (2020) to post COVID and during an energy crisis (2023), on environmental conditions (indoor thermal comfort in winter and summer, relative humidity, and concentration of CO_2), satisfaction and their relevance. In addition, specific questions about natural ventilation and the relevance of heatwaves impacts in the buildings are included in the surveys.

2.5 Analysis of data

For monitoring data, mean hourly data per classroom of selected rooms in each high school, selecting only learning schedules was studied. In the museum, all data of mean hourly data of selected rooms during all days, due to the main purpose of a museum, that is the maintenance of their collections. The study is based on boxplots of mean hourly data of all spaces of each building, comparing four winters. Also a comparison of energy consumption in the buildings with available data adjusted by HDD is done, and a summary of the responses of the surveys per kind of building.

3 RESULTS

3.1 Case Study 1. High School IES.NV

IES.NV had some monitoring data of indoor temperatures and CO_2 concentration prior to the pandemic, and all teachers and staff were very aware of the benefits of having data to improve environmental conditions and allow face to face learning of adolescents. Figure 2 shows the potential of a very conscious natural ventilation done manually in classrooms during the two years of the pandemic (mean 1.000ppm), and how it decreased from mean values higher than 2.500ppm in a pre-pandemic winter. However, and following the feedback of the teachers, CO_2 values have increased after the pandemic (1.500ppm mean values), because there is less awareness of the relevance of an adequate IAQ for the education and well-being of adolescents and adults, and due to the concern of trying to balance indoor temperatures with an exponential increase in energy costs. Temperatures are lower than adequate for educational purposes in all the studied winters, as it is stablished in the standards (e.g. the set point in Spain is 21ºC, for new schools).

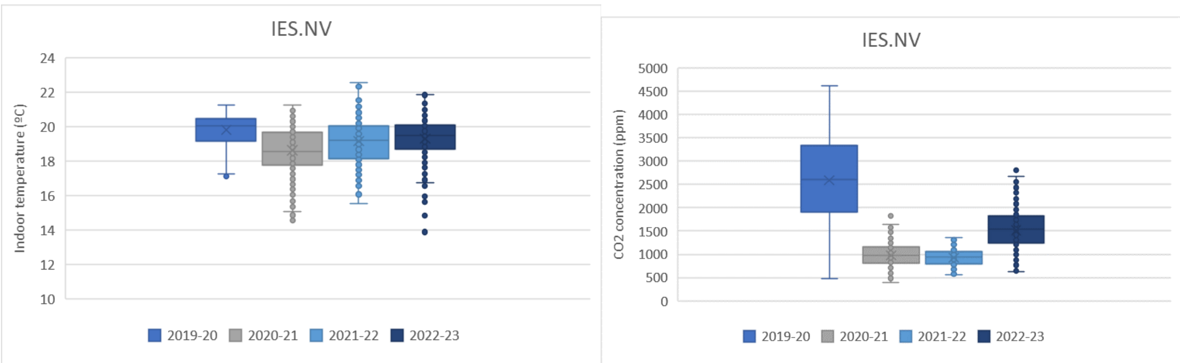

Figure 2: Monitoring data in IES.NV High School during winter months (Dec. to Feb.) of 4 years. Hourly mean values in selected classrooms of indoor temperatures (left) and CO_2 concentration (right)

3.2 Case Study 2. High School IES.PC

IES.PC had only two winter monitoring data, one during pandemic restrictions and the second one during the post pandemic situation. CO_2 concentration presents a similar situation than in IES.NV (Figure 3). During pandemic mean values of CO_2 concentration was 1.000ppm, and in the post pandemic and energy crisis situation the school has mean values near 1.500ppm. It should be noted this similarity, taking into account the differences in occupancy rates due mainly to the higher volume in IES.PC in relation to IES.NV, that should had allowed a better IAQ. Mean temperature during pandemic was lower than 19ºC, and the winter post Covid has better adequate mean values for a school, higher than 21ºC

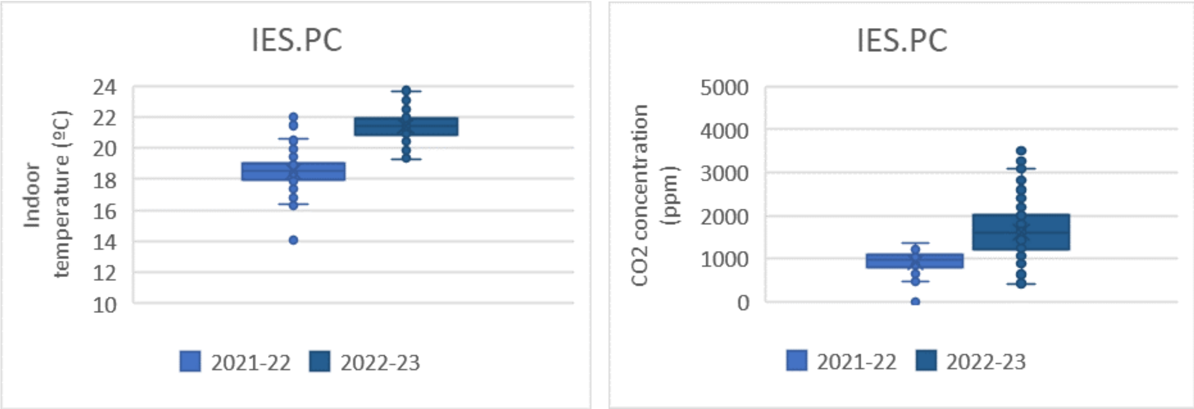

Figure 3: Monitoring data in IES.PC High School during winter months (Dec. to Feb.) of 2 years. Hourly mean values in selected classrooms of indoor temperatures (left) and CO2 concentration (right)

3.3 Case Study 3. Museum MN

MN has a monitoring system for more than 10 years mainly focused on the maintenance of their collections, therefore only with indoor temperature and relative humidity. Data of all building through mean hourly selected data during all hours of the three coldest winter months is shown in Figure 4. Temperatures are slightly higher that 19ºC during the first three studied years, with a significant difference during the last year, being lower.

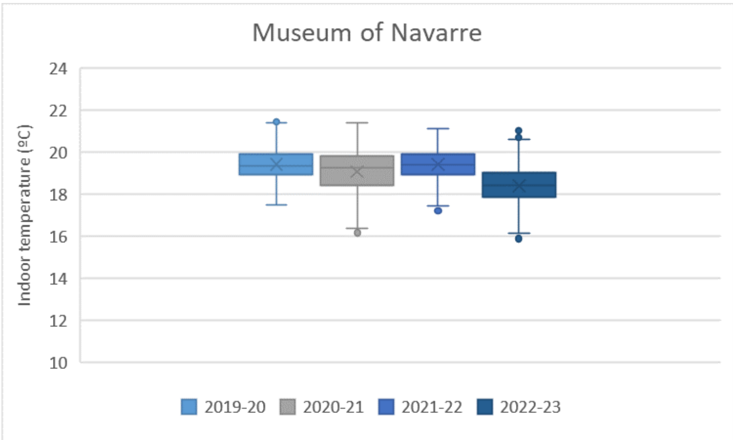

Figure 4: Monitoring data in Museum of Navarra during winter months (Dec. to Feb.) of 4 years. Hourly mean values in selected rooms of indoor temperatures

3.4 Heating energy consumption

Heating energy consumptions of the four studied winters and in two buildings (the museum and IES.NV) are analyzed in relation to the winter 2018/19 previous to the pandemic, and is summarized in Table 5.

During winter 2019/20, both buildings have 15% and 13% less, due to all buildings closed in Spain due to COVID emergency, on March 15th. During COVID, to obtain the difficult balance of minimum acceptable temperatures and the lowest CO_2 concentration to minimize illness risks, High school IES.NV has 31-27% more of normalized energy consumption. However, the museum had only a little impact on the first year, due to the use, the rates of occupancy, and the low rates of natural ventilation, due to the requirements for the conservation of collections. Finally, during Winter 2022/23, heating energy consumption has decreased in both buildings even in respect to the base year 2018/19, between 8-11%, due to the energy crisis and the final of the COVID emergency. As natural ventilated buildings, this decrease in energy consumption resulted in the detriment of environmental conditions, and specially in relation to IAQ. It should be noted, that in this study, differences in final bills have not been studied for not having the final values.

Table 5: Sumary of heaing consumption in the high school IES.NV and in the museum MN

	Winter	Heating consumption kWh/m² annual	HDD (15ºC)	kWh/m² per degree day	Normalized kWh/m² annual	% variation in relation to winter 18/19 (pre COVID)
IES.NV	2018/19	68,4	1516	0,0451	70,74	
	2019/20	50,4	1310	0,0385	60,32	-15%
	2020/21	79,43	1488,6	0,0593	93,00	+31%
	2021/22	88,49	1548	0,0572	89,62	+27%
	2022/23	57,43	1376,8	0,0417	65,40	-8%
MN	2018/19	60,47	1516	0,0399	62,54	
	2019/20	51,21	1310	0,0391	61,29	-13%
	2020/21	73,28	1488,6	0,0492	77,18	+9%
	2021/22	67,79	1548	0,0438	68,66	-3%
	2022/23	55,06	1376,8	0,0400	62,70	-11%

3.5 Surveys to personnel in charge

Finally, 11 surveys were obtained from building staff (directors and secretaries, and maintenance staff) and managers (from the public and regional administration); 4 from the museum (including one from the collection restorer in charge), and 7 from both High Schools. A summary of them is summarized in Figure 5.

Questions related to the change in perception and summarized in Figure 5 are as follows (1-5, not important to very important):

1. Before COVID, how important was to obtain in the buildings adequate temperatures in winter? and in the actual situation?
2. Before COVID, how was your satisfaction in relation to indoor thermal conditions in winter? how is it in the actual situation?
3. Before COVID, how important was to obtain in the buildings adequate temperatures in summer? and in the actual situation?
4. Before COVID, how was your satisfaction in relation to indoor thermal conditions in summer? how is it in the actual situation?
5. Before COVID, how important was to obtain in the buildings adequate ranges of relative humidity? and in the actual situation?
6. Before COVID, how was your satisfaction in relation to relative humidity? how is it in the actual situation?
7. Before COVID, how important was to consider CO_2 concentration in your building? and in the actual situation?
8. Before COVID, how important was to naturally ventilate your building? and in the actual situation?

Questions related to the perceived importance on different measures to upgrade the buildings, that are summarized in Figure 5, are as follows (1-5, not important to very important):

a. Substitution of oil boilers with renewable energies
b. Renovation and improvement of the control and regulation of the heating system
c. Installation of a new air conditioning system
d. Installation of mechanical ventilation system
e. Improvement or substitution of windows
f. Improvement or substitution of shading
g. Add insulation on opaque facades
h. Add insulation on roofs
i. To include more nature in the environment
j. To reduce or eliminate traffic around the building

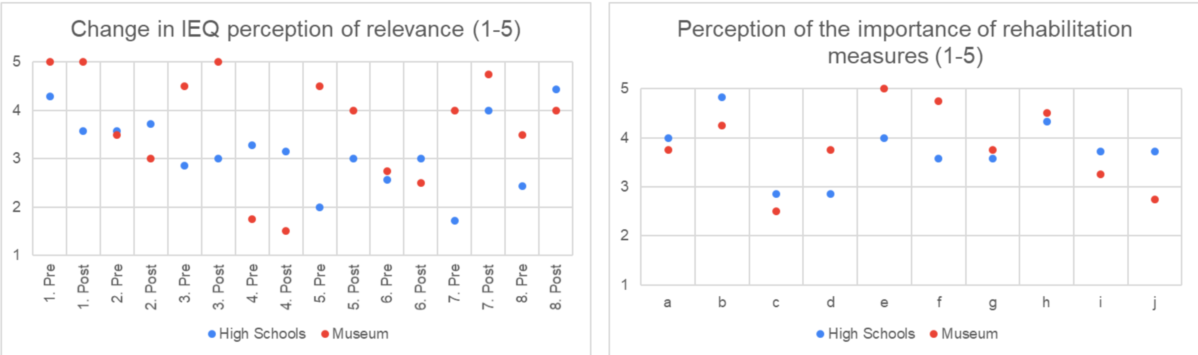

Figure 5: Graphs with summary of surveys results

From the answers of the surveys emerge mainly the change from prior COVID to post COVID and actual energy crisis, on the relevance in schools on indoor air quality (from 1,7 to 4) and natural ventilation (from to 2,4 to 4,4). However, some of them regret how fast awareness about IAQ have decay due to the urgency of maintain minimal temperatures with affordable costs, at the moment the main concern in these buildings.

Due to the specific use of each typology of buildings, there are clear differences between them, even having oil boilers and lacking mechanical ventilation and air conditioning. AC systems are not perceived as relevant in the two kinds of buildings, nor mechanical ventilation in schools. However, an improvement in the heating system, renewable energies and an improvement in the control of the system in the three case studies are the preferred upgrades. In the museum, the preferences for renovation of windows, shadings and insulation in roofs stands out regarding upgrade of thermal envelopes, while in the schools, insulation in roofs.

4 DISCUSSION

Natural ventilated existing buildings require an upgrade especially those with high demanding IEQ requirements, as schools and museums, Staff have to balance thermal comfort, IAQ and energy consumption in a different way according to the different events that have influence buildings worldwide. Upgrade of buildings with HVAC systems are needed but the potential of passive NV should be harnessed not only to rely on energy consumption. In addition, the benefits of mechanical ventilation on IEQ are not well understood as other studies found, probably due to noise, additional energy consumption and difficult of use(Monge-Barrio et al., 2022).

More studies in existing buildings are needed to allow to understand the potential and challenges of natural ventilated buildings during external events that can compromise adequate indoor environmental quality, and therefore wellbeing of occupants.

5 CONCLUSIONS

This study explores building energy behaviour and indoor environmental conditions during four years with different external events that have been taking place at global level from 2020, as the COVID pandemic (2020-2022) and the energy crisis (mainly from the war in Ukraine from February 2022). During these events, existing naturally ventilated buildings had to balance minimum thermal comfort, high levels of ventilation (to reduce CO_2 concentration and risk of infection) and low energy costs. Museum and schools are typologies of non-residential buildings highly demanding but with different requirements.

This study presents three case studies, two high schools and a museum, in a location with a temperate climate in the North of Spain. The analysis is based on heating energy consumption and monitoring data from 2019 (previous to the COVID pandemic), during 2020/2021 and 2021-22 (during COVID pandemic) and during 2022-23 (without any COVID restrictions and during an energy crisis). In addition, the study includes the analysis of questionnaires to the staff, regarding their switch of their environmental perceptions and priorities. Data shows how high level of CO_2 concentration prior to COVID pandemic, are followed by two years of low and adequate levels for a NV buildings during COVID (mean values of 1000ppm). However, after pandemic CO_2 concentration have risen due to the new concerns of the energy costs in the two case studies (to mean values of 1500ppm). Indoor temperatures have been balanced during COVID to the minimum with high energy consumption (up to 30%) even accepting low temperatures for the benefits of face to face learning. However, energy crisis has reduced energy consumption around 10% from pre-COVID consumption affecting IEQ in both kinds of buildings. The relevance of IEQ have risen through the COVID pandemic, although the perception of the upgrade of HVAC systems are mainly focused on the heating system and the renewables and not on mechanical ventilation. Much more research is needed on the performance of existing buildings specially those as schools and museums with high IEQ requirements.

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