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Relevance of CO_2 based IAQ Indicators: Lessons from a Long-term Monitoring of two Nearly Zero Energy Houses

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ABSTRACT

France is committed to minimizing its greenhouse gas emissions by focusing on the most energy-consuming sector, the residential and tertiary building sector. The renovation of existing buildings and the construction of energy efficient ones are therefore proposed as a possible solution. However, the concept of efficiency is ambiguous and difficult to measure and compare without common parameters and indicators. Indeed, a performance indicator is a decision support tool that describe the specific situation of something based on certain parameters. This article focuses on the Indoor Air Quality (IAQ) measure in new nearly zero energy houses, based on CO_2 as a parameter. We reviewed the literature, standards and regulations in order to identify a selection of 10 CO_2-IAQ performance indicators. We calculated each of them using a long term monitoring dataset (3 years) from two connected and occupied nearly zero energy houses in France (COMEPOS project). We performed the calculation during the heating seasons, in the living rooms and the parental bedrooms. Each room was equipped with a low-cost CO_2 concentration sensor sampling every minute. We compared the indicators values between them and to the thresholds of different requirements in order to highlight the relevance and the limits of the information provided by those common CO_2-IAQ performance indicators. According to the selected indicator, the IAQ is differently classified (good/poor) in the two houses at the same room and year. The preliminary evaluations in bedrooms show a difference of 20-34% on the average concentration and a difference of 28-70% on the cumulative exposure greater than 1000 ppm. Thus, a house can be characterized differently depending on the indicator and the years evaluated.

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INTRODUCTION

The interest in the Indoor Environmental Quality (IEQ) of the dwellings has increased as people spend more time at home. Possible risks to the health related to IEQ have been detected in Energy-retrofitted buildings (Ortiz, Itard, and Bluyssen 2020) and experimental campaigns in zero-energy buildings and in multi-unit residential buildings suggest that the Indoor Air Quality (IAQ) has the greatest influence on the IEQ (Danza et al. 2020; Andargie, Touchie, and O'Brien 2019). Nevertheless, the IAQ lack of consensus on measurement parameters and limits to assess the performance of buildings (Salis et al. 2017). Nearly 100 parameters are used to describe the quality of the thermal, acoustic, and visual environment in the green buildings schemes (Wei et al. 2020). Due to the complexity and impracticality of calculating diverse indicators of different standards using several parameters, we propose to focalize in one widely used parameter: the CO_2 concentration.

The CO_2 concentration is already proposed as parameter for the IAQ evaluation in standards such as NF EN 15251, NF EN 15665 and NF EN 16798 (CEN 2017; NF EN 15251 2007; NF EN 15665 2009). Although the indoor CO_2 concentration is not an IAQ indicator, it is well known as an indicator of occupancy, air renewal and air stuffiness (Persily 2017; Ribéron et al. 2016; ANSES 2013). However, the calculation and interpretation of the CO_2-IAQ indicators are difficult due to a lack of consensus in the reference values, periods, time step, occupancy scenarios and places to measure.

We present 10 CO_2-IAQ indicators selected from the literature, standards and regulations, and we focus in two of them: the mean concentration and the cumulative exposure greater than 1000 ppm. Both indicators were calculated from the COMEPOS project database of two connected, real and occupied nearly zero energy houses in France, during three heating seasons (CEA-INES 2021).

MATERIALS AND METHODS

Case studies: two low-energy houses

The study houses where the samplings and measurements (from late 2017 to early 2020) were conducted are located in the Paris region in France. *Table* 1 presents the characteristics of the houses and Figure 1 shows their plans. The selected periods are the heating seasons between November 1 and April 15. These dates were chosen according to the degree-day (Park, Shim, and Song 2021) of the three years and the periods in which there is an electrical consumption related to heating in the houses.

Table 1: Characteristics of the COMEPOS houses

	House 1	House 2
Location	Paris region in France	
Total area	106 m²	147 m²
Number of bedrooms	4	4
Number of humid rooms	3	5
Living room area	40 m²	40 m²
Parental bedroom area	9 m²	26 m²
Ventilation system	Humidity-controlled ventilation B type	
Inhabitants	2 adults and 1 child (2018) 2 adults and 2 children (2020)	2 adults and 3 children
Occupancy data	An adult is not present every day because of his work A child was born in 2020	An adult work at night

Figure 1: Plans of the study houses.

Smart ventilation systems

The houses have a smart demand-controlled ventilation (DCV) system (Durier, Carrié, and Sherman 2018). More specifically, they have a humidity-controlled exhaust-only ventilation system, which is a DCV system widely used in France. In this system, the new air enters through humidity-controlled air inlets located in bedrooms and living rooms, and is extracted in humid rooms equipped with humidity controlled exhaust vents, except in the toilets where occupancy sensors are used. The extensions and retractions of a hygroscopic fabric modify the cross-section of inlets (trickle ventilators on windows) and exhaust vents on relative humidity (RH). This ventilation system is further described by Jardinier et al. (Jardinier et al. 2018). At this stage, there are no information about the real ventilation rates in the houses.

IAQ sensors

Each house is equipped with the E4000 NanoSense probe (Nanosense n.d.) for measuring temperature, RH and CO_2 concentration. The manufacturer's specifications indicate that the measuring range and the accuracy are [0-50°C] and ±0.3°C for the temperature sensor, [10-90%] and ±3% for the RH sensor and [390-3500 ppm] and ±100 ppm at 25°C and 1013mbar for the CO_2 sensor. We focus in the CO_2 measurements. Three years of data with a time step of one minute using this probe are available for the study.

Data analysis and quality validation

We cleaned the data with a three-step treatment:

- Removal of CO_2 concentration out of [390-3500 ppm] and with a ΔCO_2 higher than ±100ppm/min. Both conditions were chosen taking into account the accuracy and measuring range of the probe.
- Suppression of identical values for more than 60 consecutive minutes.
- Sampling of the data over a time step of 10 minutes by retaining the average value. The average is calculated only if there are at least half of the values in the interval.

Table 2 presents the percentage of data available before the treatment (%DBT) and after the treatment (%DAT). The % DBT shows how many data is obtained by the low cost captors but also the extent to which the measurements are representative of the period. There are more than 70%DBT in each season in the two rooms of both houses. The %DAT indicates how many of the initial data is usable, it ranges from 45 to 89% and is the indicator used in the rest of our analysis.

Table 2: Percentage of data available before treatment (%DBT) and after treatment (%DAT) for the heating seasons in the COMEPOS houses. Time step of 10 minutes. Living room (LR) and parental bedroom (PBR)

House	Room	Heating season 2017-2018 %DBT	2017-2018 %DAT	2018-2019 %DBT	2018-2019 %DAT	2019-2020 %DBT	2019-2020 %DAT
House 1	LR	99	83	100	89	70	46
	PBR	99	66	100	49	70	45
House 2	LR	83	67	95	68	98	75
	PBR	83	69	95	77	99	83

IAQ indicators calculation based on CO_2 measurements

A performance indicator is a decision support tool that describe the specific situation of something based on certain parameters. The calculation of these indicators combined with reference values allows the information to be compared and framed. In this study, the CO_2 data provided by the E4000 probe is the parameter and the thresholds of different requirements are the reference values. We compare the results of the indicators calculated in the two houses in order to determine if they lead us to the same conclusions and to identify the important thresholds for evaluating the IAQ performance of a dwelling.

The ten following indicators, from the literature, standards and regulations, were calculated in the living room (LR) and the parental bedroom (PBR) during the heating seasons:

1. the mean concentration (Ministerio de Fomento 2019; NF EN 15251 2007; NF EN 15665 2009) described in Equation 1.
2. the mean concentration above a threshold value (NF EN 15665 2009) described in Equation 2.
3. the percentage of time spent in a concentration range (Guyot 2018; J. Laverge, Pattyn, and Janssens 2013; NF EN 13779 2007; NF EN 15251 2007).
4. six types of cumulative exposures greater than a threshold value (BCCA 2012; CCFAT 2015; Guyot, Walker, and Sherman 2018; Jelle Laverge 2013; Mansson 2001; Ministerio de Fomento 2019; NF EN 15665 2009). The cumulative exposure greater than a threshold value indicator, which is similar to the notion of "dose", makes possible to accumulate exposure beyond a threshold over a given period. While the dose is calculated for one person, this indicator is calculated on a room scale. It is widely used to assess the performance of intelligent ventilation systems, with nuances depending on different countries (Guyot, Walker, and Sherman 2018). Equations 3-8 describe the CO_2 cumulative exposure indicators and the corresponding threshold values if they are available, considering an average outdoor concentration of 350 ppm. The E_{1050} and E_{1750} reference values could be consulted in (Mansson 2001).
5. the ICONE air stuffiness index (Ribéron et al. 2016) described in Equation 9. This index is calculated with the frequencies of time spent in the concentrations ranges, between 1000 and 1700 ppm and above 1700 ppm. The scale of the index goes from 0 to 5 where 0 corresponds to no stuffiness and 5 to extreme stuffiness.

The reference values vary according to the indicator. Some reference values are constant (E_{950}, E_{1600} and E_{2000}), variables (E_{1000}), between ranges (percentage of time spent in a concentration interval, E_{1050}, E_{1750} and ICONE air stuffiness index) or non-specified (mean concentration). In the case of the mean concentration indicator, which has not a recommended reference value, we propose to use one of the most common IAQ-CO_2 threshold: 1000 ppm (ANSES 2013; Von Pettenkofer 1858).

$$C_{co_2\,avg} = \frac{\sum_i C_{co_2}(t_i)}{\sum_{tot} i} \tag{1}$$

$$C_{avg\ co_2 > threshold} = \frac{\sum_i C_{co_2} > threshold\ (t_i)}{\sum_{tot} i} \tag{2}$$

$$E_{950} = \sum_{t=0}^{T} \left(C_{CO_2 > 950ppm}(t) - 950ppm \right) \cdot t \; < \; 100\,000 \text{ ppm.h} \tag{3}$$

$$E_{1000} = \sum_{t=0}^{T} \left(C_{CO_2 > 1000ppm}(t) \right) \cdot t \; < \; 1000 \text{ ppm} \cdot X \tag{4}$$

$$E_{1050} = \sum_{t=0}^{T} \left(C_{CO_2 > 1050ppm}(t) \right) \cdot t \tag{5}$$

$$E_{1600} = \sum_{t=0}^{T} \left(C_{CO_2 > 1600ppm}(t) - 1600ppm \right) \cdot t \; < \; 500\,000 \text{ ppm.h} \tag{6}$$

$$E_{1750} = \sum_{t=0}^{T} \left(C_{CO_2 > 1750ppm}(t) \right) \cdot t \tag{7}$$

$$E_{2000} = \sum_{t=0}^{T} \left(C_{CO_2 > 2000ppm}(t) \right) \cdot t < 400\,000\ ppm.h \tag{8}$$

$$ICONE = 8{,}3 \log(1 + f_1 + 3f_2) \tag{9}$$

To avoid the underestimation of certain indicators, it is recommended to calculate them only considering the exposure periods. That is asses the time in which occupants are in the rooms. However, obtaining and coding this information is difficult and when this data is not available or it is not precisely enough, it is necessary to use an occupancy scenario. Table 3 describes the occupancy scenario used to calculate the CO_2-IAQ indicators, which is derived from the literature (Guyot 2018; Zeghnoun, Dor, and Grégoire 2010).

Table 3: Occupancy scenario for the calculation of CO_2-IAQ indicators. Living room (LR) and parental bedroom (PBR)

Room	Occupancy hours
LR	07h00 to 08h30; 12h00 to 14h00; 19h00 to 21h00
PBR	21h00 to 06h20

In this paper, we focus on two performance indicators: the mean concentration and the cumulative exposure greater than 1000 ppm. The other indicators are further developed in a recently published work (Rueda López et al. 2021).

RESULTS AND DISCUSSION

CO_2 mean concentration

Figure 2 shows the mean CO_2 concentrations in the LR and the PBR for each heating season. All the average values in both houses, in both rooms, and during the three heating seasons are in the range of [743-1482 ppm].

In House 1, the mean concentrations are below the 1000-ppm threshold in the LR during the three heating seasons at 792, 769, and 743 ppm, respectively. The threshold is only exceeded in the PBR during the 2017 and 2019 heating seasons at 1360 and 1135 ppm, respectively. The lower concentration of 898 ppm found in 2018 could be explained by occupancy changes: One of the adults in this house is not present every day because of his work, which implies that the CO_2 sources were sometimes the half.

In the LR of House 2, the mean concentrations are close to the 1000-ppm threshold during the three heating seasons at 1003, 1058, and 950 ppm, respectively. The threshold is always exceed in the PBR during each heating season at 1482, 1478, and 1185 ppm, respectively. The lowest average concentration recorded in House 2 in both rooms was in the 2019 heating season.

In the LRs, the CO_2 mean concentrations varies little during the heating seasons in the two houses, from 6 to 10%. In contrast, in the PBRs these variations are greater, from 20 to 34%. The difference between LRs and PBRs during the heating seasons are 14–42% in House 1, and 20–32% in House 2.

Although the two houses have the same ventilation system and similar volumes in LRs, there is a significant variation between their mean concentrations, from 21 to 27% depending the heating season. In the PBRs, the volume differs considerably: the PBR volume of House 2 is almost three times greater than that of House 1. Based only in the volume of the room, we expect to found higher concentrations in the PBR of House 1 than in the PBR of House 2, but it is not the case in any of the heating seasons. The variation between PBRs are 8% in 2017, 39% in 2018, and 4% in 2019.

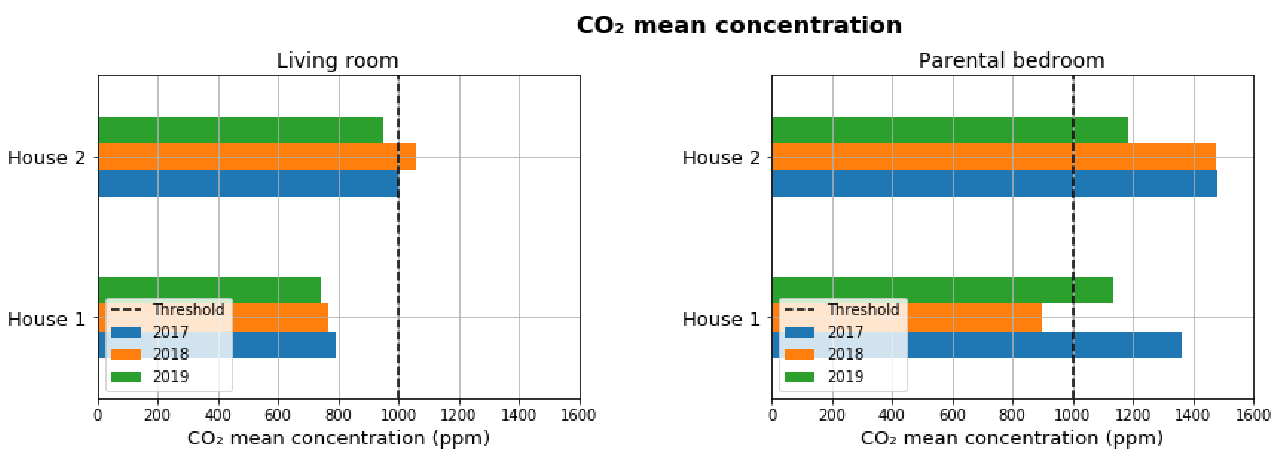

Figure 2: CO_2 mean concentrations in the living room and parental bedroom. 1000-ppm threshold.

Cumulative exposure greater than 1000 ppm

Table 4 summarizes the results and thresholds of the cumulative exposure greater than 1000 ppm (E_{1000}) in the LR and PBR of both houses during three heating seasons. The thresholds were calculated by multiplying the simulation duration (X) in hours by 1000 ppm as marked in Equation 4. We note that none of the rooms in the two houses reaches the corresponding threshold. In fact, the thresholds are 84-93% and 51-84% greater than the E_{1000} results, in the LRs and PBRs, respectively.

Table 4: E_{1000} results and thresholds in the living room (LR) and parental bedroom (PBR) of the two houses during three heating seasons

House	Room	Heating season	E1000 (ppm·h)	E1000 threshold (ppm·h)
House 1	LR	2017-2018	251291	3310833
		2018-2019	241072	3526833
		2019-2020	125773	1831333
	PBR	2017-2018	1082574	2624833
		2018-2019	320762	1950333
		2019-2020	541460	1791833
House 2	LR	2017-2018	406105	2684500
		2018-2019	443006	2723333
		2019-2020	368711	3008000
	PBR	2017-2018	1358179	2761667
		2018-2019	1480075	3082333
		2019-2020	1060291	3327833

Figure 3 represents graphically the E_{1000} results in each house among the heating seasons. The variation between the results in the same house through the heating seasons are greater in the PBRs than in the LRs. In LRs, these variations are up to 50% in House 1 and up to 17% in House 2. In the PBRs, the variations are up to 70% in House 1 and up to 28% in House 2.

Similar to the previous indicator (mean concentration), PBRs have higher air stuffiness than LRs, which implies that the IAQ in LRs is better than in PBRs. Indeed, the difference between rooms ranges 25-77% in House 1 and 65-70% in House 2.

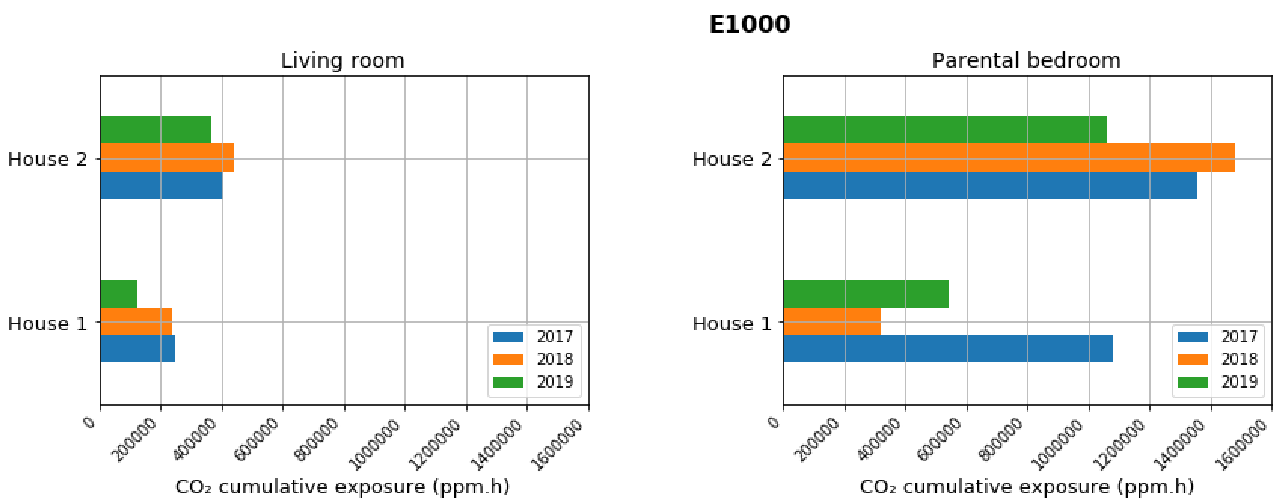

Figure 3: Cumulative exposure greater than 1000 ppm (E_{1000}).

Analysis of results and discussion on the relevance of indicators

The results of the application of numerous CO_2-IAQ performance indicators in two real, similarly ventilated, near located and inhabited houses, during several heating seasons provides an approach to the assessment of the IAQ.

We found that the same house in the same heating season can be characterized as lightly confined by one indicator and highly confined by another. An example of this disparity is the PBR of House 2, where the air has a high stuffiness level according to the mean concentration and a low stuffiness level according to E_{1000}. This, therefore, questions the relevance of the indicators, their construction and the reference values to classify the IAQ. In fact, the reference values of the different indicators are not linked to each other and the regulations that proposes them rarely justify them.

There is also a temporal variability of the results: A room can be considered lightly confined according to a specific indicator during one heating season and be characterized highly confined during another heating season. An example is the PBR of House 1 where the mean concentration reveals that the air has a high stuffiness level in 2017 and 2019 and a low stuffiness level in 2018. The same trend is visible in the LR of House 2 with the same CO_2-IAQ performance indicator. These variations can be mainly explained by changes in the habits of the inhabitants since no malfunctioning of the ventilation system has been reported.

CONCLUSIONS

There is a large number of IAQ indicators based on CO_2 measurements but not all of them are sufficiently defined since they lack of reference values and measurements protocols, which leads to an ambiguity in the calculations and in the interpretation of results. We consider that a quality indicator must be quantifiable but also comparable to be exploitable.

Even if all the indicators are based in the same parameter (CO_2 concentration) and are all calculated with a same database, they give different results, which can be contradictory. The same house can be characterized differently at the same period depending on the indicator, the threshold chosen and the room evaluated (parental bedrooms usually have a higher stuffiness than living rooms).

Depending on the years, the preliminary evaluations in bedrooms show a difference of 20-34% on the average concentration and a difference of 28-70% on the cumulative exposure greater than 1000 ppm. Thus, a house can be characterized differently depending on the indicator and the years evaluated.

Some perspectives of this work are the measurements of the ventilation performances (flow rates, pressures differences, visual inspection) in each house and the calculation of IAQ indicators based on relative humidity and VOC measurements.

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NOMENCLATURE

$C_{CO_2}: CO_2\ concentration\ in\ ppm$

$f_1: proportion\ of\ C_{CO_2}\ between\ 1000\ and\ 1700\ ppm$

$f_2: proportion\ of\ C_{CO_2}\ above\ 1700\ ppm$

$t: time\ in\ hours$

$X: number\ of\ data\ available\ after\ treatment\ or\ simulation\ duration\ in\ hours$

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