IEA EBC Annex 68 - Indoor Air Quality Design and Control in Low Energy Residential Buildings – Setting the Metrics

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SUMMARY
This paper presents the initial reflections in the frame of Subtask 1 – Setting the Metrics of the IEA EBC Annex 68 – Indoor Air Quality Design and Control in Low Energy Residential Buildings. The first step of IEA Annex 68 aims at summarizing the current knowledge on target pollutants for residential buildings and at evaluating indoor air quality (IAQ), i.e. how to define indices that provide useful information allowing to achieve low risks for health in indoor spaces, and how to enable the comparison of solutions for achieving high IAQ taking into account energy efficiency. At this stage of the project, there is no single definition of the metric that would allow meeting these objectives. However, the potential elements of such definition presented in this paper regarding both IAQ and energy indices will be further investigated in the course of the project.

PRACTICAL IMPLICATIONS
The present paper provides the current state of knowledge pertaining to the assessment of performance of residential buildings considering specifically IAQ and energy. In particular, target pollutants, IAQ indices and associated energy use are presented.

KEYWORDS
Indoor air quality, residential building, energy, ventilation, air cleaning

1 INTRODUCTION

To achieve nearly net zero energy use, both new and energy refurbished existing buildings will need to be even more efficient and optimized in the future. As such buildings can be expected to be well insulated already, airtight, and have heat recovery systems, one of the next focal points to reduce energy use will possibly be the reduction of ventilation rates, or efficient way of using ventilation, e.g. by using demand controlled approaches. However, this must be attained so that at the same time no adverse effects on indoor air quality (IAQ) are introduced. The new project under IEA's Energy Conservation in Buildings and Communities Programme (EBC) aims to investigate how to ensure that future low energy residential buildings will secure improved energy performance and at the same time provide comfortable and healthy indoor environments. Among others, new paradigms for demand control of ventilation and other ventilation solutions will be investigated. Pollution loads and occupancy in buildings will be considered as well. Thermal and moisture conditions in the future advanced buildings will also be included, because of interactions between the hygrothermal parameters, the chemical composition and ventilation, which all affect the wellbeing of occupants.

IEA EBC Annex 68 project is divided into five subtasks: (1) defining the metrics, (2) pollutant loads in buildings, (3) modelling, (4) strategies for design and control of buildings, and (5) field measurements and case studies. The starting point and one of the primary purposes of Annex 68 is the first subtask, as it sets the frame for defining the parameters that can be optimized and their limits. This paper presents the approaches to complete the work defined in this subtask.

2 METHODS

The objectives of Subtask 1 will be achieved by compiling and analysing previous studies on the subject available in the literature. A first step will consist of determining a list of target pollutants commonly found in residential buildings and by identifying the pollutants that are listed by cognizant authorities as harmful. It will be verified whether they are present in residential environments at the concentrations, which can surpass the recommendations of the different authorities. Since the 1980s, guideline values for pollutants typically found in buildings have been proposed. These values are based on consensus reached by the multidisciplinary groups of experts studying the toxic properties and health effects of these pollutants following the comprehensive review and thorough evaluation of accumulated scientific evidence. Additionally, the existing IAQ metrics will be reviewed to propose the scientifically sound index (or set of indices) for the evaluation of indoor air pollution. Different endpoints will be considered and the metric scheme(s) defined. The last part of this subtask will be dedicated to examining the energy implications of the proposed metric scheme(s) to ensure that there is no unreasonable increase of energy consumption.

3 RESULTS

Target pollutants

Due to the high number of pollutants found in indoor environments, it is first necessary to group the most important ones in terms of their health effects. Recent studies have used similar approaches as indicated below: literature review, setting up criteria to select compounds, review of exposure and dose/response data, risk characterization of the selected compounds and prioritization of the selected compounds. In this way, the World Health Organization (WHO, 2010), the European INDEX project (2005) and the French IAQ Observatory (OQAI, 2010) established the lists with target pollutants in indoor air. Benzene, carbon monoxide, formaldehyde, naphthalene, nitrogen dioxide, particulate matter (PM) and polycyclic aromatic hydrocarbon (PAH) are clearly identified as the high priority target pollutants. The French IAQ Observatory (OQAI, 2010) undertook from 2003 to 2005 a national survey in French dwellings collecting measuring data for 30 parameters (chemical, biological and physical) in 567 dwellings, representative of the French housing stock. The pollutants were then ranked using the following equation:

$$I = I_{acute} + I_{chronic} + I_{frequency} \quad \text{with} \quad I_{acute} = f\left(\frac{C_{\max}}{MRL_a}\right) \text{ and } I_{chronic} = g\left(\frac{C_{mean}}{MRL_c}\right) + I_k \tag{1}$$

where I is the hierarchical index (0 to 20), I_{acute} and $I_{chronic}$ are the indices relative to the acute and chronic health risks and range from 0 to 5 and 0 to 10, respectively. $I_{frequency}$ is the index relative to the presence frequency in the residential indoor air (0 to 5). I_{acute} depends on the ratio of the maximal concentration (C_{max}) and the minimum risk level for acute effects (MRL_a). $I_{chronic}$ accounts for the chronic effect potential using the mean concentration (C_{mean}) and the minimum risk level for chronic effects (MRL_c) and the carcinogen risk (I_k) that is equal to 0 if there is no effect and 5 if effects on human are proved.

Thus, a substance that is classified higher in the ranking system, as its hierarchical index is close to 20, is more prevalent and more harmful for health. In other words, its average and maximum concentrations are close to the limit values pertaining to chronic and acute exposures, and the probability that it is present in the building is high. This method has the advantage that it is easier to comprehend as all compounds are ranked by one number only. However, there is no scientific basis for addition of health risks related to acute effects (high concentration, short time) and chronic effects (low concentration, long-time). According to health agencies, they need to be considered separately. This is a limitation of the method.

Recently, Djouad et al. (2015) established the list of target pollutants for office buildings and hospitals using up-to-date pollutant reference values and concentrations measured in-situ obtained by reviewing literature. Figure 1 presents the list of pollutants for residential buildings established using Djouad et al. methodology and the data of the national survey in French dwellings. PM is clearly the most important pollutant to be considered for acute health effects (75%). Carbon monoxide, acrolein, formaldehyde, and radon should also be considered. The result for chronic exposure is quite different. Ranking of PM reduced to 35% and the ranking of formaldehyde, acrolein, and nitrogen dioxide are about 20% each. Benzene and radon also play a notable role.

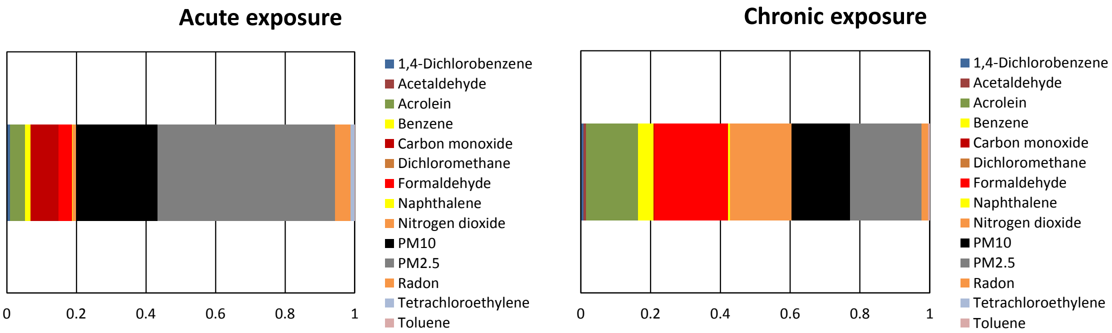

Figure 1. Relative importance of indoor pollutants for residential building sector (left: acute exposure, right: chronic exposure); the data based on study by Djouad et al. (2015).

The data on concentrations of pollutants from the studies mentioned are from buildings built before 2006. These levels and the type of pollutants can be different in new low energy buildings. Derbez et al. (2011) showed that concentrations of VOCs were up to 10 times higher for some components in 7 new low energy houses compared to data of OQAI (2010). The current project will (due to lack of sufficient data and measurements) focus to the extent possible on pollutants and their concentrations measured in low energy buildings.

IAQ Metrics

Once the list of target pollutants is established, the right metric to evaluate the IAQ has to be defined. According to Sofuoglu and Moschandreas (2003), an index of IAQ must be able to communicate indoor air pollution levels to a non-scientific audience, must be correlated to the symptoms experienced by the occupants and should be used as a management tool to improve effectively air quality. A literature review of existing indoor environmental quality indices has been recently carried out by Kirchner et al. (2006). Overall, the IAQ indices considered different pollutants, exposure limits and aggregations of effects. Based on Kirchner et al. (2006), the different indexes can be classified into four categories (Table 1):

Category 1: One index per pollutant

A dimensionless index is defined by dividing the measured/calculated concentration by a reference value. The reference value usually relates to health (accounting for chronic or acute effects), but other metrics can also be used (e.g., odor threshold). A value higher than one, i.e. a concentration higher than the reference value, warns about a potential IAQ problem. An index is calculated per pollutant. The approach has been used by Cohas (1996).

Category 2: Simple aggregation

One unique index is calculated as the sum of all indices evaluated as for Category 1. Gadeau (1996) and Castanet (1998) used this simple algebraic calculation to establish one index. In the definition of an Indoor Environment Index (IEI), Chiang and Lai (2002) calculated an IAQ sub-index based on the average of grades (from 20 to 100) according to the pollutant concentrations (see Table 1 with an example for CO_2).

Category 3: Aggregation according to the pollutant sources or types

The French project QUAD-BBC (2012) used the simple aggregation principle dividing the measuring results according to 4 groups related to the pollutant sources or types (Figure 3, left graph): human presence (A), cooking activity (B), potential sources of gaseous pollutant in the studied room (C) and particles (D).

Category 4: Aggregation accounting for the IAQ of the building stock

The Indoor Air Pollution Index (IAPI) developed by Sofuoglu and Moschandreas (2003) is estimated from the averaged concentration of 8 pollutants: VOCs (formaldehyde and TVOC), inorganic gases (CO and CO_2), particulate matters ($PM_{2.5}$ and PM_{10}) and biological particles (bacteria and fungi). Sub-indices are aggregated using arithmetic mean in conjunction with a tree-structured calculation method. The main feature that makes IAPI different from the previous indices is that it includes the pollutant concentration ranges (minimum and maximum values) measured during the Building Assessment Survey and Evaluation project (Girman et al., 1995) that was focused on office buildings.

Accounting for energy consumption

This section aims at evaluating the additional energy consumption needed to improve IAQ. The main solutions to reduce the pollution concentrations in indoor spaces that can be energy costly: increasing the amount of outdoor air and/or use of air cleaners and pollutant entrapment with hoods or exhausts. Pollution source control will not increase operational costs for energy, or can even reduce this cost, but may be difficult to realize during renovations.

Increasing outdoor air supply rate will increase energy needed to condition (heat, cool, humidify or dehumidify) the outdoor air. Considering a ventilation system with heat recovery typically found in low-energy building, the energy demand can be calculated as follows:

$$Q_{load} = \rho \times c_p \times Q_v \times (1-\varepsilon_x) \times (T_{in} - T_{out}) \tag{2}$$

where Q_{load} is the energy demand (W), ρ is the air density (kg/m^3), c_p is the air heat capacity (J./(kg.K)), Q_v is the volumetric air flow rate (m^3/s), ε_x is the heat exchanger efficiency (-) and T_{in} and T_{out} are the indoor (or supply) and outdoor temperatures (K), respectively.

Increasing the ventilation air or using air cleaner in the ventilation system such as additional or more efficient particle/gas filters (resulting in a pressure loss increase), will have a direct effect on the fan electric consumption. The fan electric power can be expressed by:

$$P_{fan} = \frac{Q_v \times \Delta p_{fan}}{\varepsilon_{fan}} \quad \text{or} \quad P_{fan} = \frac{Z}{\varepsilon_{fan}} Q_v^{\,3} \tag{3}$$

where P_{fan} is the electric power used by the (W), Δp_{fan} is the fan total pressure difference (Pa), ε_{fan} is the fan overall efficiency (-) and Z overall pressure loss coefficient (kg/m^7).

Table 1. IAQ indices.

Cat.	Reference	Pollutant	Equation
1	Cohas (1996)	Any	$$I_{BILGA} = \begin{cases} \max\left(\frac{E^P_{mean} - MRLc^P_T}{MRLa^P_T - MRL^P_T}\right) si\ E^P_{moy} > MRLc^P_T \\ \max\left(\frac{E^P_{mean} - MRLc^P_T}{MRLc^P_T}\right) si\ E^P_{moy} \leq MRLc^P_T \end{cases} \quad (4)$$ where E^P_{mean} is the mean exposure to pollutant p over the period of time T and $MRLc^P_T$ and $MRLa^P_T$ are the Minimum Risk Levels for chronic and acute effects.
2	Gadeau (1996)	CO, CO_2, NO_2, Formaldehyde	$$I_{CLIM2000} = \frac{1}{4}\left(\frac{[CO]}{30} + \frac{[CO_2]}{4500} + \frac{[NO_2]}{0{,}4} + \frac{[HCHO]}{0{,}06}\right) \quad (5)$$ where concentrations are in mg/m^3.
	Castanet (1998)	CO, CO_2, Bacteria	$$I_{LHVP} = \frac{[CO]}{5} + \frac{[CO_2]}{1000} + \frac{[Bacteria]}{1000} \quad (6)$$ where *[CO]* and *[CO_2]* are carbon monoxide and dioxide concentration (ppm) and *[Bacteria]* is the bacteria concentration (cfu/m^3).
	Chiang and Lai (2002)	CO, CO_2, Formaldehyde, TVOC, PM_{10}	$$I_{IEI\_IAQ} = \frac{1}{p}\sum_{i=1}^{p} Grade_i \quad (7)$$ where $Grade_i$ is 20, 40, 60, 80 or 100 depending on the pollutant concentration values. Example for CO_2: $Grade_i = 20$ if [CO_2] > 2500 ppm, $Grade_i = 40$ if 2500 ppm > [CO_2] > 1000 ppm…
3	QUAD-BBC (2012)	Group A: CO_2 Group B: NO_2, SO_2, O_3 Group C: CO, Formaldehyde, Acetaldehyde, Ethylbenzene, Styrene, Toluene, o-Xylene, Acetone Group D: $PM_{2.5}$, PM_{10}	$$I_{QUAD-BBC} = \sum_{i=1}^{p} \frac{C_{obs}}{C_{dmc}} \quad (8)$$ where *p* is the pollutant number in the group, *dmc* is the demarcation concentration and *obs* is the measured concentration.
4	Sofuoglu and Moschandreas (2003)	Formaldehyde, TVOC, CO, CO_2, $PM_{2.5}$, PM_{10}, Fungi, Bacteria	$$I_{IAPI} = \frac{1}{I}\sum_{i=1}^{I}\frac{1}{J}\sum_{j=1}^{J}\frac{1}{K}\sum_{k=1}^{K} 10 \times \left[1 - \frac{C^{\max}_{i,j,k} - C^{obs}_{i,j,k}}{C^{\max}_{i,j,k} - C^{\min}_{i,j,k}}\left(\frac{C^{dmc}_{i,j,k} - C^{obs}_{i,j,k}}{C^{dmc}_{i,j,k}}\right)\right] \quad (9)$$ where *I* is the number of level-3 groups, *J*, the number of level-2 groups in each level-3 group, *K*, the number of level-1 pollutant variables in each level-2 group and *max* and *min* are the measured maximum and minimum concentrations, respectively.

Electric energy use can also be in relation to active air cleaning devices that employ techniques such as electrostatic precipitation, plasma or photocatalytic destruction.

Final energy can be evaluated once the duration of using the ventilation system is known. The total energy can then be evaluated after conversion to primary energy consumption.

As an example, the primary energy consumption for a low-energy residential building has been used to evaluate the energy cost of two IAQ solutions (Table 2). Simulations were made during the QUAD-BBC project (2012). The buildings were located in France, equipped with a conventional balanced system with heat recovery and heated by electric devices. Increase in the total primary energy consumption (heating + fan electricity consumption) by 59% and 35% were seen for a 50% increase of the airflow rate and when a F7 filter was added in the system, respectively. This simple calculation shows that improving IAQ can have an important impact on energy consumption. This example is a simple illustration. A real energy consequences will depend on the whole ventilation system equilibrium, fan control, fan type, age of filters. An investigation made by Stephens et al. (2010) shows that upgrading a ventilation system to a higher level of filtration can actually either induce higher or lower energy consumption.

Table 2. Simulation of the potential energy penalty to improve IAQ in a low-energy dwelling.

Energy consumption for heating (kWh_{pe}/m^2.year)	Envelope	Ventilation	Fan	Total	Increase
Reference	17	8	6.1	31.1	
Increasing ventilation rate by 1.5*	17	12	20.6	49.6	59%
Increasing filter efficiency (G4 to G4/F7)*	17	8	17.1	42.1	35%

*exchanger nominal efficiency = 0.85, constant fan efficiency, G4 to G4/F7 pressure loss increase = 100 Pa (initial pressure loss = 125 Pa)

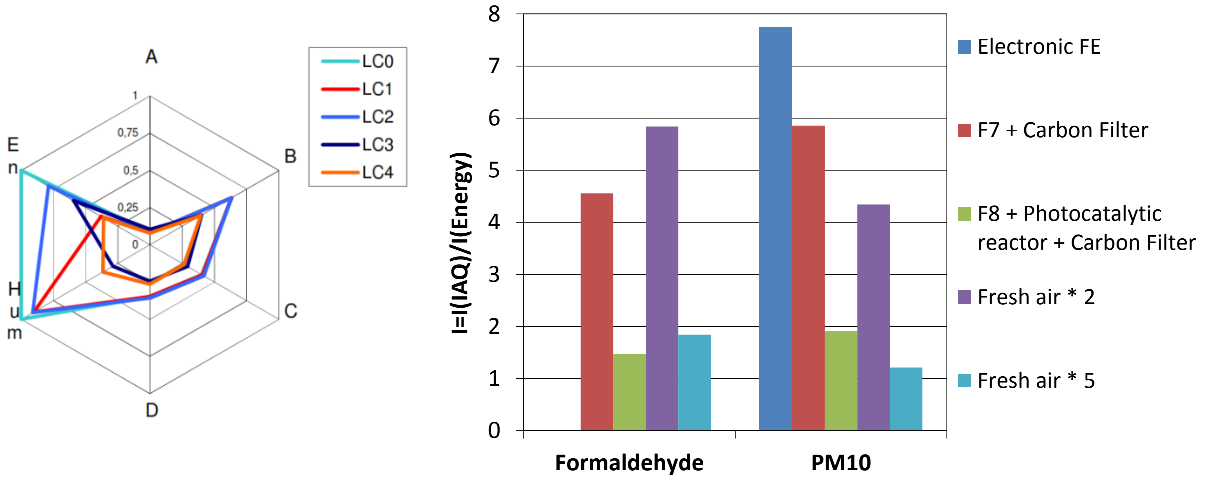

Figure 2. Accounting for energy consumption in IAQ evaluation (left graph: *A, B, C and D* are IAQ indices, *Hum* is relative to humidity and *En* is the energy index, 0 is the best situation for IAQ and energy; right graph: the index aggregates IAQ and energy, 0 is the worst situation because of bad IAQ, high energy consumption or both).

Some studies have included energy use in their evaluation of solutions to improve the air quality of indoor spaces. In the QUAD-BBC project (2012), IAQ indices and energy use have been considered separately. The left graph of Figure 2 presents the chosen approach where the indices obtained for different ventilation configurations (LC0, LC1…) are represented in a radar graph. *A*, *B*, *C* and *D* are IAQ indices (see Table 1), *Hum* is defined as the ratio between the percentage of hours with relative humidity above 75% and *En* is the energy index. This index is dimensionless and obtained by dividing the primary energy consumption of the considered configuration by the maximum possible energy use. In this example, LC4 (a balanced system with heat recovery and occupancy-based airflow rate) is clearly the best solution in terms of IAQ and energy consumption. Tourreilles (2015) used a unique index to compare the different solutions. This index is defined as the ratio of an IAQ index (0 being bad, 1 being good) to an energy one (0 being the solution with the lowest additional energy consumption). In this way, the best solution in terms of IAQ/energy use has the index highest value. In the example shown in Figure 2, the electronic filter is clearly the best choice for PM but is the worst one for formaldehyde (no effect on formaldehyde concentration). The "F7+Carbon Filter" and "doubling the fresh air rates" solutions are equivalent to treat both formaldehyde and PM while the two other solutions induce too high energy consumption.

4 DISCUSSION

Producing a short list of pollutants of interest is not easy as it relies on the current exposures to pollutants in the indoor environments and on current evidence regarding allowable health/toxic limits. There can perhaps be new pollutants in future buildings and the occupational/health/toxic limits for pollutants need to be revised as well. If we use the current state of knowledge, few substances clearly emerge as the pollutants of concern. These are: $PM_{2.5}$, PM_{10}, formaldehyde, benzene and nitrogen dioxide, and PAHs. These pollutants are frequently found in residential buildings and have multiple sources; many are related with pollutants in ambient air. Other pollutants already regulated or included in the guideline need to be considered on a case-by-case basis: radon is geographically dependent (presence of granitic soil), as is tetrachloroethylene (proximity of a dry cleaning facility), carbon monoxide is mainly due to incomplete combustion process, and naphthalene in residential buildings mainly comes from mothballs. Biological pollutants, such as molds, are considered separately and no dedicated guideline values are available. WHO did not set guidelines for moisture except for recommendations that the moisture must be avoided. The mold needs to be considered because of its toxic potential and the high prevalence in residential buildings.

Some aggregation of the IAQ indices developed for individual pollutants needs to be made should the simple index be established. One unique index may not be the ultimate solution as demonstrated in QUAD-BBC (2012). However, considering the goal of the current project and potential future application of the index for designing and controlling IAQ in residential building, and also acceptance by practice, the development of a simple index is a key element.

Accounting for energy to evaluate different solutions can be done either separately or by aggregation with IAQ indices. In all cases, the main problem is to define the relative importance between additional energy consumption ($kWh_{pe}/m^2 \cdot year$) and IAQ benefit, in other words how much it costs to improve IAQ in terms of energy (kWh/index unit). Recent studies evaluated the years of life lost by premature mortality or disability due to specific indoor pollutants (Hänninen and Knol, 2011) or the cost of indoor air pollution (ANSES, 2014) that is about €300/inhabitant/year (€219 only due to particles) in France. These methodologies and results need to be considered in the present work to actually judge the relevance of a solution on an IAQ/energy basis.

5 CONCLUSIONS

This paper attempts to summarize the initial work of data compilation and reflections about the best way of evaluating the IAQ level of residential buildings. At this point, there is some understanding of the target pollutant list that needs to be considered because of their negative effects on health and well-being. There is also some understanding of how the performance of different solutions to improve IAQ should be compared. However, the attempts to define the metrics that best account for IAQ and associated energy use should continue because no common metric that is widely approved by different stakeholders has been established so far.

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