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SMART-RENO-IEQ: Exploring the Capabilities of Low-Cost Sensors to Evaluate PM2.5 Exposure in Single-Family Houses

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In building energy renovation, the notion of payback time of the investments is often presented as the only goal. However, the potential benefits in terms of health are also valuable despite being not consciously perceived by the occupant and may need to be monitored to be assessed. Laboratory-grade devices or protocols are generally burdensome and expensive, and the growing popularity of low-cost devices may contribute to the perception of health benefits at a larger scale.

This study takes part in the 6th subtask of the French research project Smart-Réno-IEQ (2019-2021) on the impacts of energy retrofits on indoor thermal and air quality of single-family houses. This paper aims at exploring the capabilities of these low-cost sensors to evaluate PM2.5 exposure. The focus is not put on their real-time accuracy, but on their ability to be consistent with laboratory-grade systems to estimate short to long-term indoor air quality indicators as ULR-IAQ or DALY.

Measurements of eight low-cost devices, raw sensors or commercial integrated solutions, have been compared to laboratory-grade equipment, in the lab-house EUREKA (TIPEE, France). Exposure scenarios have been recreated from realistic occupant activities, such as cooking, use of electrical or gas heaters, cleaning events, walking, use of aerosols, candles or incense, smoking and handiwork.

The commercial devices have shown better consistency than most raw sensors and provided similar indicator estimations than the reference device. Accuracy of low-cost sensors is dependent on the nature of the emission source, but these devices generally show a better prediction of exposure indicators on recreated scenarios than on a particular experiment.

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INTRODUCTION

In building energy renovation, the main advertised value is generally the payback time of the investments. However, the expected energy savings are not always achieved and tend to lower the expected gains. One of the explanations is a behavior change of the occupants as they may trade part of their savings for more comfort. Therefore, the value of the renovation exceeds the sole economic considerations. The potential benefits in terms of health are also a possible claim when one seeks to better understand the perceived value of an energy retrofit operation. Nevertheless, Indoor Air Quality (IAQ) is not consciously perceived by the occupants and the pollutants need to be monitored to be assessed. The most truth worthy methods use laboratory-grade devices or burdensome protocols that are generally expensive. The growing popularity of low-cost devices may contribute to the perception of health benefits at a larger scale.

This study takes part in the 6th subtask of a larger scale French research project: Smart-Réno-IEQ (2019-2021) on the impacts of energy retrofits on indoor thermal and air quality of single-family houses. The goal is here to explore the capabilities of these low-cost sensors to evaluate the exposure on particulate matter and more particularly the PM2.5.

Most of the studies evaluating low-cost particle sensors (Airlab, 2018; Spinelle, 2018; Mouradian, 2018; Walker et al., 2018), although showing their potential, conclude on one of their major obstacles to overcome: reliability of their measurements and the limitations of their detection capabilities. However, the health benefits are generally estimated through long term exposure indicators, and the focus is not put on the real-time accuracy.

This paper describes a methodology adopted to evaluate the ability of low-cost particle sensors to be consistent with laboratory-grade systems to estimate short to long-term indoor air quality indicators as ULR-IAQ or DALY (Cony Renaud Salis, 2020). An example of its application is presented and discussed.

METHODS

Two experimental campaigns had been carried out in September and December 2020 in the lab-house Eureka (TIPEE) to compare the behavior of low-cost particle sensors and a laboratory-grade system towards realistic exposures to PM2.5. In this section, the lab-house, the sensors, the pollutant sources, and the global methodology will be described.

Description of the lab-house Eureka (TIPEE)

The lab-house is a two-story house (figure 1) located in Lagord (France).

Figure 1 Lab-house Eureka (TIPEE).

Two rooms have been isolated (door and windows closed): a 30 m^3 bedroom and a 170m^3 living room with an incorporated kitchen. A controlled air change rate of 0.5 has been monitored during the experimentation (15 m^3/h for the bedroom and 85 m^3/h for the living room). The air is mixed thanks to one fan for the bedroom and two fans for the living room (figure 2).

Figure 2 Bedroom (left) and living room (right).

Sensors

Eight low-cost devices, raw sensors or commercial integrated solutions, have been compared to a laboratory-grade equipment (Mini-Wras, Intertek). The Table 1 illustrates the sensors used. The brands and visuals are voluntarily hidden in respect of the commercialism policy. Nevertheless, a short description is provided as many similar devices are available commercially.

Table 1. Sensors used in this experiment.

Sensors	Short description
Raw low-cost sensors	**Light scattering LASER sensors with a fan. Very low cost: about 20 euros, small size. Integrated on an Arduino system for this study.**
RS1 – brand 1	PM data: PM1, PM2.5, PM10 - 53x38x21 mm
RS2 – brand 1	PM data: PM1, PM2.5, PM10 - 48x37x12 mm
RS3 – brand 1	PM data: PM1, PM2.5, PM10 - 38x35x12 mm
RS4 – brand 2	PM data: PM2.5, PM10 - 71x70x23 mm
RS5 – brand 2	PM data: PM2.5, PM10 - 43x32x25 mm
Commercial integrated solutions	**Ready to use, an interface and a software are included. Low cost: about 200 euros. Other parameters are monitored by these systems, we consider exclusively the PM data.**
CIS1 – brand 3	PM data: PM2.5
CIS2 – brand 4	PM data: PM1, PM2.5, PM10
CIS3 – brand 5	PM data: PM2.5
Laboratory-grade equipment (reference)	**Short description**
REF – brand 6	PM data: 10 channels between 10nm and 193nm (electric mobility spectrometer) 31 channels between 253 nm and 35 µm (light scattering measuring cell)

Global methodology and indicators

The sensors (Table 1) have been placed near each other and a large variety of sources (Table 2) has been used in the two rooms described previously.

Table 2. Short description of the sources.

Sources	Short description
Presence of an occupant	Passive or active (walking) – bedroom and living room
Cooking episodes	Oven and electric hob, toast - living room
Cleaning	Broom, vacuum cleaner, dust removal - bedroom and living room
Aerosols	Perfumes, deodorant - bedroom
Comfort	Incense, candles - bedroom
Vaping	Vaping - bedroom
Heaters	Heaters (gas and electric) - bedroom
Domestic work	Wood, metal and plastic cutting and sanding - living room

For each source, the PM2.5 concentration in the room has been monitored with both the low-cost sensors and the laboratory-grade system. A database has been created with the mean concentration measured by each equipment during a representative time for each activity (Table 3).

Once this database completed, it is possible to construct different weekly scenarios for the occupants. In this paper three simplified examples are taken to illustrate the methodology (Table 3). A base-case scenario (scenario 1) is compared to two other scenarios including respectively incense and vaping episodes.

The last step is to evaluate the final exposure through IAQ indicators and compared the results obtain for each low-cost sensor with the reference system. The Figure 3 illustrates this global methodology.

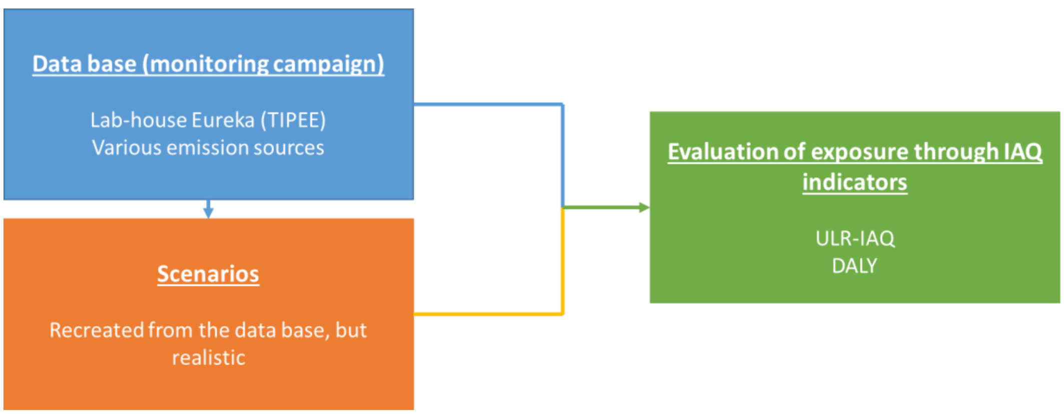

Figure 3 Description of the global methodology.

Table 3. Description of three simplified scenarios (hours per week of each activity)

Source	Scenario 1 (h)	Scenario “incense” (h)	Scenario “vaping” (h)
Cooking	3.5	3.5	3.5
Presence of an occupant - walking	21	21	21
Aerosols	2.3	2.3	2.3
Incense	0	4	0
Vaping	0	0	2,3
Mean background concentration	141.2	137.2	138.9

Two indicators have been selected. The “ULR-IAQ” ($I_{ULR-IAQ}$), developed at the University of La Rochelle (Cony Renaud Salis, 2020), is based on the long term and short-term exposure limit values. Since only one pollutant is considered, the sub-indicator for PM2.5 is used (equation 1).

$$I_{ULR-IAQ,i} = 10 \times \frac{C_{int,i} - ELV_{LT,i}}{ELV_{ST,i} - ELV_{LT,i}} \quad (1)$$

Where : i: pollutant i (here PM2.5), C: indoor concentration

$ELV_{LT,i}$: long term exposure limit values considered for PM2.5 (10 µg/m^3) :

$ELV_{ST,i}$short term exposure limit values considered for PM2.5 (25 µg/m^3)

The DALY is a long-term exposure indicator representing the number of years of life expectancy lost per 100,000 inhabitants. A description of the calculation methods can be found in the work of Logue et al. (2011). An IAQ Indices tool developed by the IEA EBC Annex 68 (Cony and Abadie, 2019) has been used for the calculation.

RESULTS

For each activity/source of each scenario (Table 3), a mean exposure is considered. The process is illustrated Figure 4 for the use of incense in the bedroom. In the next part of this paper, only 3 low-cost sensors, of different brands, will be considered to simplify the analysis as some of them have similar behaviors. The selected sensors and the pertinent results are sum up Table 4.

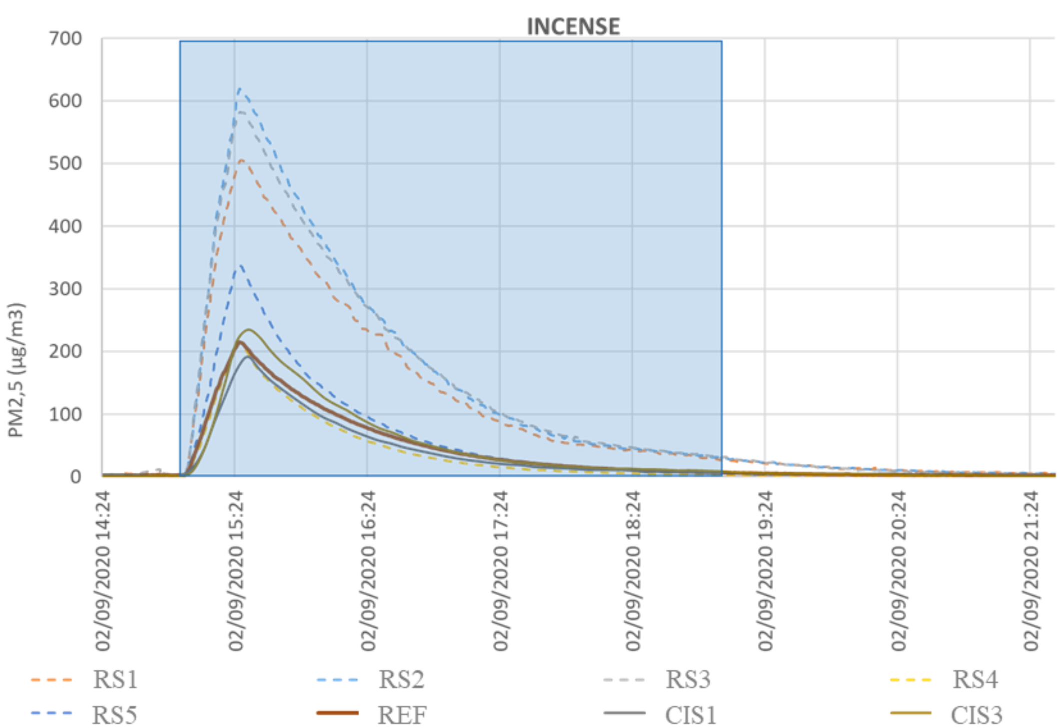

Figure 4 Example of the database for one source (Incense in the bedroom) and the 4h hour period considered.

Table 4. Mean exposure, concentration for each activity used to create exposure scenarios from Table 3.

Source	PM2,5 - REF (µg/m^3)	PM2,5 – CIS1 (µg/m^3)	PM2,5 – RS2 (µg/m^3)	PM2,5 – RS4 (µg/m^3)
Cooking	21.7	25.6	37.15	22.1
Presence of an occupant - walking	9.8	11.93	25.15	0.93
Aerosols	52.9	42.7	71.76	33.34
Incense	102.7	80.46	97.55	340.26
Vaping	812.7	609.1	539.75	562.7
Mean background concentration	9.2	11.5	2,1	4,1

The figure 5 illustrates the raw data of Table 5. The hierarchy between each source is respected on every considered sensor. Nevertheless, the detection ratios vary among the low-cost sensors. For example, the RS2 seems to overestimate the exposure due to incense but, on the contrary, underestimates the sources due to resuspension (walking episodes). These differences may be partly hidden regarding the weekly exposure, as compensation may occur.

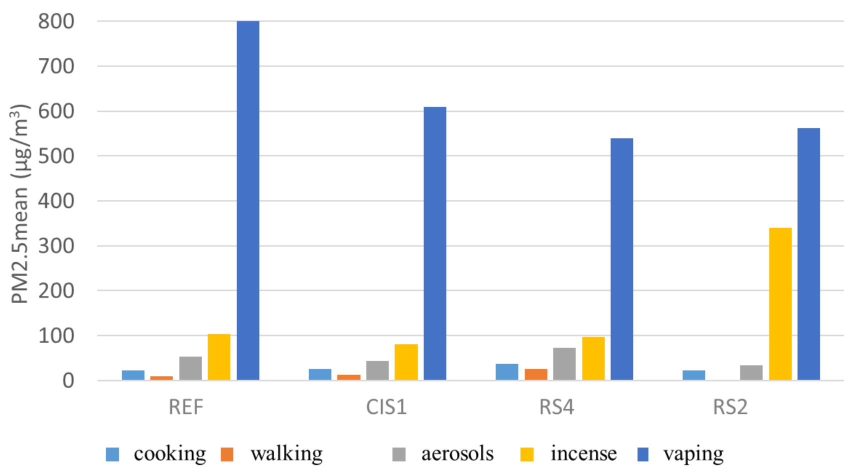

Figure 5 Raw data of the data base for each activity and each considered sensor.

For each scenario, the weekly mean exposure concentration has been calculated (Figure 6). Figure 7 represents the absolute difference, from the scenario 1, on the same data.

In all scenarios, the CIS1, a commercial integrated solution, presents better results than the raw sensors (RS2 and RS4). These sensors were used without recalibration for the measurement in an indoor environment whereas the sensors integrated in the CIS1 may have been specifically recalibrated and their signals are maybe post-processed/adjusted before they are sending back to the user.

Regarding the DALY calculation, the CIS1 shows a particularly good correlation with the reference system. Due to the structure of the ULR-IAQ (its value is 0 if the mean concentration is under the long-term exposure limit of 10 µg/m^3) it presents a larger gap on this indicator, especially for the scenario 1 (the mean concentration is near the long-term exposure limit). Nevertheless, they both show a good quality of air, and the conclusions would be the same.

Regarding the raw sensors, they globally underestimate exposure in every scenario. Figure 5 shows that, for example, the RS2 fails to detect the background concentration increase during walking episodes. The high concentration events, such as the use of incense, are on the contrary well detected but represents only a short period during the week. This event partly compensates the other sources for the overall exposure but is not sufficient.

It seems that the inability of these sensors to access the exposure during background or low-concentration periods plays a large part in the global underestimation. A specific calibration could be considered to enhance these results.

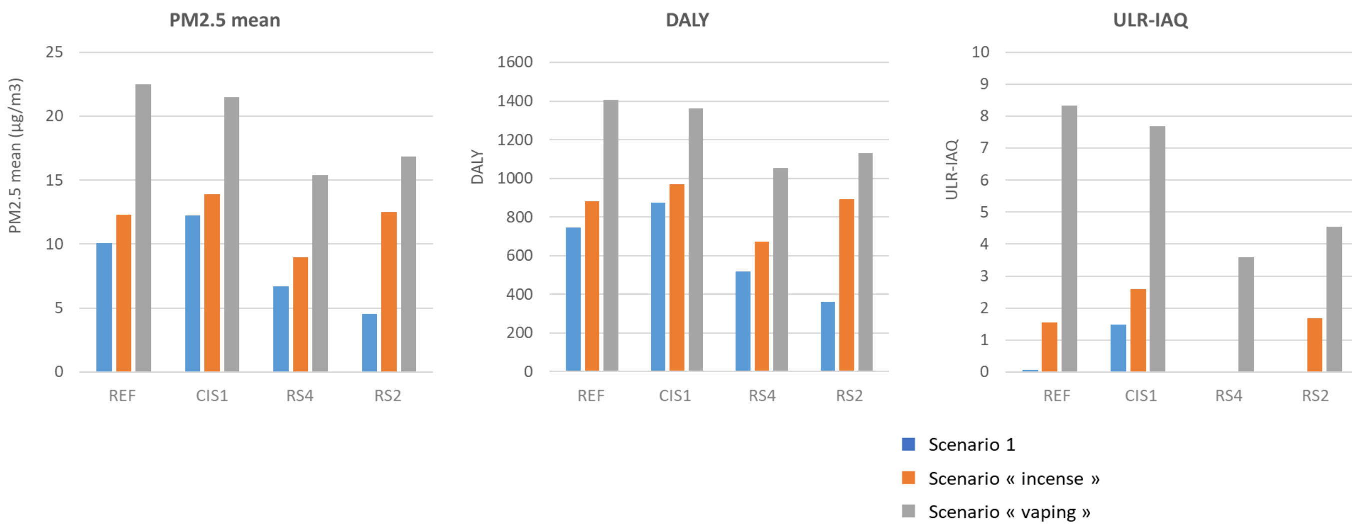

Figure 6 Results for the mean concentration of PM2.5 and the two considered exposure indicators. Three low cost sensors are illustrated with the reference system (REF).

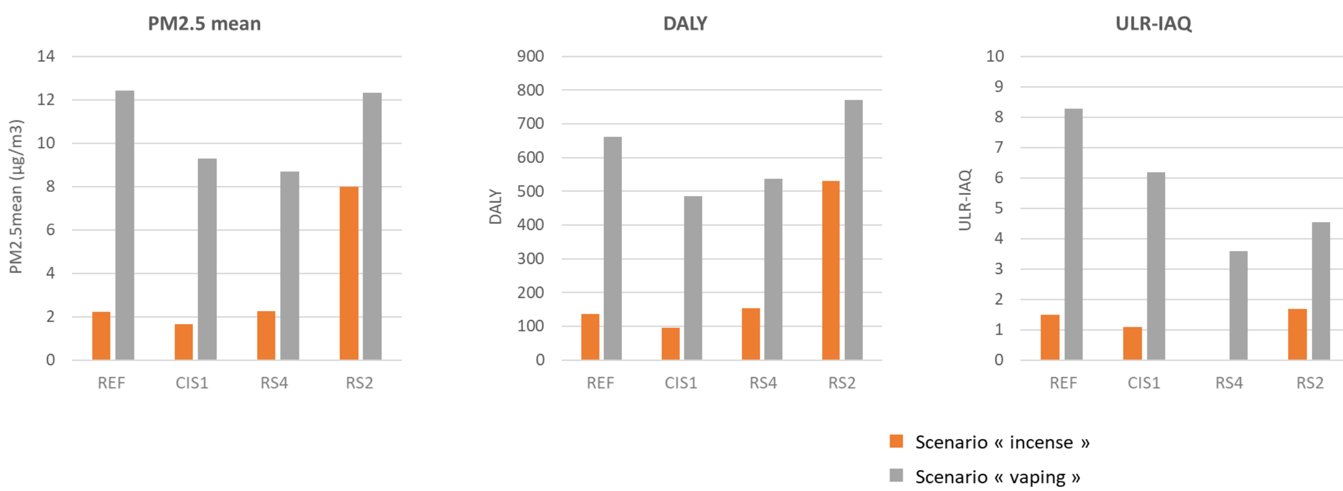

Figure 7 Absolute difference, from the scenario 1, for the mean concentration of PM2.5 and the two considered exposure indicators.

CONCLUSION

This paper presents the principles of a methodology to evaluate the capabilities of low-cost sensors to evaluate PM2.5 exposure in single-family houses.

The construction of the scenarios presents several limits as it, for example, does not consider the exchanges between the rooms and the synergy between the sources. Nevertheless, the goal is not here to estimate the exposure of occupants but to compare low-cost sensors and lab-grade systems on realistic levels of PM2.5.

The commercial devices have shown better consistency than most raw sensors and provided similar indicator estimations than the reference device. Accuracy of low-cost sensors depends on the nature of the emission source. High pollution events are generally well detected, but a global underestimation of exposure can be observed, due to difficulties to detect low pollution periods.

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