Indoor air quality in social housing flats retrofitted with heat pumps

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SUMMARY
The UK Government is planning large-scale deployment of domestic heat pumps, yet there is limited data on the indoor air quality (IAQ) implications of moving to low carbon heating. This paper undertakes empirical measurement of IAQ before and after smart heat pump retrofit in five naturally-ventilated social housing flats in Oxford. Plug-in Airthinx sensors monitored IAQ parameters including CO_2, Particulate Matters ($PM_{2.5}$, PM_{10}), formaldehyde (CH_2O) and Volatile Organic Compounds (VOCs: ethanol and Isobutylene), temperature and relative humidity (RH) in the living rooms of all flats during the heating season, for one week before and one week after heat pump installation. While indoor temperatures were more stable post-retrofit, indoor pollutants including CO_2 levels fell below 900 ppm over 90% of the monitored hours in majority of flats, mainly due to change in residents' window opening behaviour driven by constant heating provided by the heat pump. Across four flats, post-retrofit, formaldehyde levels were found to be less than WHO recommendation, while mean daily levels of PMs continued to be higher than recommended levels in three flats due to occupant smoking habit. The levels of ethanol and isobutylene showed reductions post-retrofit. It is vital that upgrades to heating system consider IAQ parameters beyond temperature and RH.

KEYWORDS
Smart heat pump, IAQ, monitoring, social housing flats

1 INTRODUCTION

To meet the net-zero carbon target by 2050, the UK Government is planning large-scale deployment of domestic heat pumps by 2030 through the 'Ten Point Plan' for a green industrial revolution (HM Government, 2020). Moving to low carbon electrification of domestic heating eliminates carbon dioxide (CO_2) through combustion, thereby potentially improving air quality (Padovani et al., 2021). Homes with heat pumps usually tend to be well-insulated to increase the efficiency of the heating system, thereby increasing air tightness levels and lowering the levels of indoor-outdoor exchange that can affect exposure to indoor air pollutants. Along with policies to phase out gas boilers and install heat pumps, the move to greater home working may have substantial effects on population exposure to indoor air pollutants and occupants' health. Despite this, there is a lack of empirical evidence on the concentration of indoor air pollutants in homes with heat pumps (BEIS, 2020). This is why a recent Government report has recommended continuous monitoring of VOCs and other indoor particulates in homes since these pollutants arise from construction materials and consumer products, and their concentration is likely to be 20 times more than outdoor pollutants (HCLG, 2019).

Low carbon heating systems coupled with renewable electricity have been found to reduce the level of particulate matters (PM) and carbon emissions to near zero (Arbon and Kilbane-Dawe, 2013). A recent study on residential space heating electrification in Ontario revealed seasonal differences in exposure to IAQ due to temperature variations (Sanongboon and

Pettigrew, 2021). In the cold season, since it is uncommon to naturally ventilate homes in order to conserve heat, air change rate was found to be less than 0.5 (Haung et al., 2014), which affected the elimination of indoor air pollutants produced from heating, cooking, smoking and washing (Alonso et al., 2022). A meta-study on exposure to indoor air pollutants in the home environment in the UK showed that main indoor air pollutants included VOCs, $PM_{2.5}$ and PM_{10}, formaldehyde, and nitrogen dioxide (NO_2) (Vardoulakis et al., 2020). Higher PM levels were reported indoors as compared to outdoor levels, indicating the impact of indoor sources including smoking and cooking (Vardoulakis et al., 2020). However, no significant association was identified between indoor pollutants and building age, size and occupancy. In another UK study, NO_2 concentrations in homes with gas cooker were measured to be double that of dwellings with electric cookers (Raw et al., 2004).

Against this context, this study conducted empirical measurement and statistical analysis of IAQ before and after installation of heat pumps in five naturally-ventilated (NV) social housing flats located in 1960s low-rise blocks in Oxford (UK). IAQ parameters such as CO_2, $PM_{2.5}$, PM_{10}, formaldehyde, VOCs (ethanol (EtOH) and Isobutylene), temperature and relative humidity (RH) were continuously monitored in living rooms of the five flats one week before and one week after heat pump installation during the heating season. The before/after paired measurements helped to reveal any changes in the concentration of IAQ parameters following the installation of heat pumps.

2 METHODS

The study used a monitoring and survey approach to examine changes in indoor air pollutants after smart heat pumps retrofit across five social housing flats located in Oxford (UK). The IAQ parameters were monitored for one week pre- and one week post-heat pump installation during the heating season from October 2020 to April 2021 as shown in Table 1 below. Household surveys were conducted to gather data on household characteristics and socio-demographics, while data on physical characteristics of the flats were extracted using Energy Performance Certificates (EPCs).

Table 1. Monitoring periods before and after heat pump installation during the heating season

Location of Flat	Flat ID	Before heat pump period	After heat pump period
Top floor flats	P03	11-Dec-20 to 17-Dec-20	07-Apr-21 to 13-Apr-21
	B05	28-Oct-20 to 03-Nov-20	24-Apr-21 to 30-Apr-21
Ground floor flats	P06	11-Dec-20 to 17-Dec-20	07-Apr-21 to 13-Apr-21
	B01	05-Nov-20 to 11-Nov-20	27-Nov-20 to 03-Dec-20
	B07	05-Nov-20 to 11-Nov-20	24-Apr-21 to 30-Apr-21

IAQ parameters including CO_2, $PM_{2.5}$ and PM_{10}, formaldehyde, VOCs (ethanol (EtOH) and isobutylene), as well as temperature and relative humidity (RH) were continuously monitored at 5-minute interval using internet-enabled Airthinx devices that were deployed in the living rooms of each flat. The devices transmitted monitoring data to a cloud-based web portal. The specifications of Airthinx devices are shown in Table 2.

Table 2. Specifications of Airthinx IAQ device

Device	Parameter	Range	Accuracy	Resolution
Airthinx	Temperature (°C)	0-99	± 0.5	0.1
	Relative humidity (RH) (%)	0-99	± 2	0.1
	CO_2 (ppm)	0-3000	± 50 +5% FS	1
	Formaldehyde(CH_2O) (mg/m³)	0-1	± 5% FS	0.001
	PM2.5/PM10 (µg/m³)	0-500	± 10% @100-500 µg/ m3	1
	VOC (ppm of EtOH)	0-10	±15%	0.01
(110 x 66x 30 mm)	VOC (ppm of Isobutylene)	0-1	±15%	0.01

The key variables in the household survey included occupant age, employment status, number of occupants, occupancy pattern, use of windows and energy use behaviour. The survey was conducted in person with social distancing protocols in place before low carbon heat pumps were installed. To avoid sharing paper, the survey was implemented using Google forms accessible through the smart phone. The data on physical characteristics of the flats (location, area, energy efficiency rating) were obtained through EPC data.

3 OVERVIEW OF CASE STUDY FLATS

The five social housing flats were located in a socially deprived area of Oxford (UK). The five flats consisted of two top floor flats (P03 and B05) and three ground flats (P06, B01 and B07) located in 1960s low rise blocks. The existing heating system was night-storage electric heaters which was upgraded to ground source heat pumps (GSHPs). The key physical and household characteristics of the flats are presented in Table 3 below.

Table 3. Characteristics of the flats (from EPCs) and households

	Characteristics	**Top floor flats**		**Ground floor flats**		
		P03	B05	P06	B01	B07
Building	Energy efficiency rating	C	C	C	C	C
	Environmental impact rating	D	D	D	D	D
	Floor area (m²)	47	33	47	33	61
Household	Number of occupants	1	1	1	1	1
	Age of resident (years)	41	50	57	63	70
	Weekday occupancy	Most of the time	Most of the time	Most of the time	24/7	24/7
	Weekend occupancy	Morning	24/7	24/7	24/7	24/7
	Employment status	Employed	Employed	Employed	Retired	Retired

The five flats varied in size ranging from 33m² in flats B01 and B05 to 47 m² in flats P03 and P06, and 61 m² in flat B07. All flats had double glazing windows with energy efficiency rating of C. Cavity walls of two flats P03 and P06 were insulated prior to heat pump installation. The flats were naturally ventilated with trickle vents in the windows and extractor fans in the kitchen and bathroom. While resident of Flat B07 regularly opened windows even in the heating season, resident of Flat B01 hardly opened the windows. The air change rate was calculated to be around 2.6 ACH using the Reduced Data Standard Assessment Procedure (RdASP) methodology. All five flats had single occupancy with weekday and weekend occupation, indicating that changes in CO_2 levels were likely to be due to window opening rather than increase in number of occupants. Figure 1 presents samples of flats' external facades (P03, P06 and B05), living room of Flat B07 and Airthinx device installed in B01.

Figure 1. Examples of flats façades (a and b), living room space and Airthinx device (c and d)

4 RESULTS

Temperature and RH

Descriptive statistics were produced to identify changes in indoor temperature and RH level pre- and post-heat pump installation. In majority of the flats, indoor temperatures were found to be more stable (narrower range) and reduced post-heat pump with daily mean temperature ranging from 20°C in P06 and B07 to 26°C in B01, while before heat pump, temperatures ranged from 23°C in B07 to 27°C in B01. Indoor RH was lowered across all flats post-retrofit with mean RH level measured as 34%, (below the recommended lower limit of 40%), as compared to 47% pre-retrofit, possibly due to the always-on nature of heat pumps leading to drying of air. Minimum RH level of 11% was recorded in P03 which also recorded minimum temperature of 20°C likely to be due to limited opening of windows in the living room.

Carbon Dioxide (CO_2) level

The CO_2 levels were found to vary across all flats pre- and post-heat pump periods, possibly due to diversity in residents' use of windows. Despite the variation, CO_2 levels were reduced across the majority of flats post-retrofit. Ground floor flat P06 and top floor flat B05 experienced significant reductions in CO_2 levels after retrofit with mean levels of 773 ppm and 626 ppm respectively (Figure 2- top), which were below CIBSE recommended level of 900 ppm for medium air quality (CIBSE, 2020), as compared to 1561 ppm (P06) and 1067 ppm (B05) in the pre-retrofit period. This reduction could be due to the observed increase in window opening of the residents to counter the always-on heating provided by the heat pumps. Despite the resident of ground floor B07 being a heavy smoker, mean CO_2 levels were measured below 900 ppm for majority of time in both periods, possibly due to resident's habit to keep windows open, in contrast to the resident of flat B01 who rarely ventilated the living room. The change in CO_2 levels pre- and post-heat pump installation were observed in the daily mean CO_2 profiles that shown in Figure 2 (bottom) indicating variations across the flats despite having similar heating systems and occupancy pattern. The occurrence of peaks and troughs did not change significantly pre and post-retrofit with CO_2 levels increasing from 4pm with peak happening during mid-night to early mornings in line with occupancy patterns.

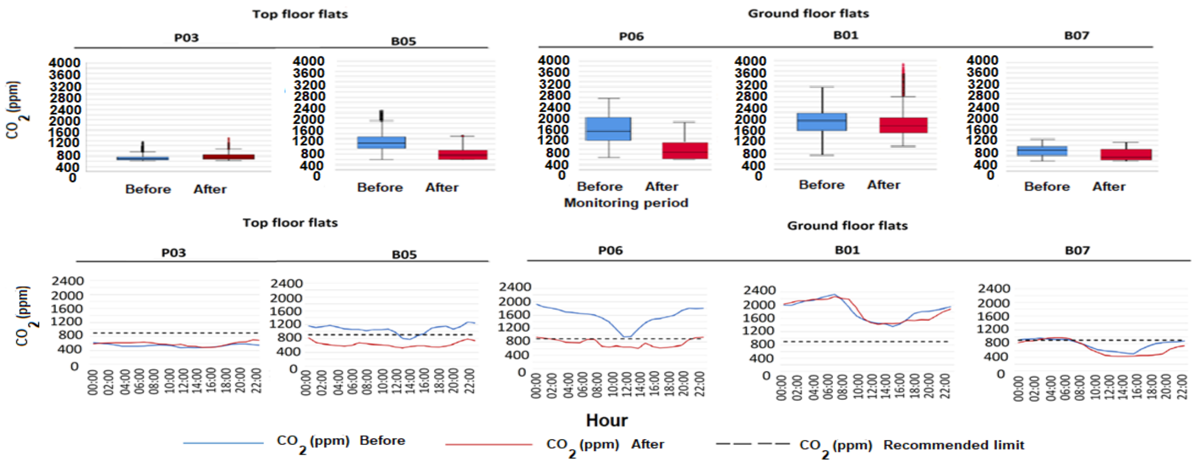

Figure 2. Distributions (top) and mean daily profiles (bottom) of CO_2 across five flats in heating season

Particulate matter ($PM_{2.5}$ and PM_{10})

The concentration of particulate matters $PM_{2.5}$ and PM_{10} was found to vary across the five flats, although the magnitude of the change pre and post-heat pump was similar in each flat (Spearman coefficient= 0.9 significant at 0.01 level). In top floor flats P03 and B05, mean levels of PMs were found to be low and below the recommended limits of 25 µg/m³ ($PM_{2.5}$) and 50 µg/m³ (PM_{10}) during a course of 24-hours (CIBSE, 2020). While the mean $PM_{2.5}$ levels in ground floor flat B05 was 7 µg/m³ pre-heat pump and reaching to 19 µg/m³ post-retrofit, in flat P03 it was recorded as 24.5 µg/m³ in both periods. The mean level of PM_{10} varied between 9 µg/m³ to 23 µg/m³ in flat B05, and around 33 µg/m³ in flat P03 pre and post-heat pump, below the recommended limit of 50 µg/m³ during a 24-hour period. On the other hand, the levels of $PM_{2.5}$ and PM_{10} in flats P06, B01 and B07 inhabited by smoking residents exceeded the recommended limits in both periods (Figure 3). Flat B01 with limited window opening experienced the highest level of PMs, with mean $PM_{2.5}$ and PM_{10} ranging from 461 µg/m³ to 528 µg/m³ respectively pre-heat pump, which increased to 521 µg/m³ and 604 µg/m³ respectively after heat pump. Daily mean profiles of PMs in P06, B01 and B07 showed the lowest level was measured between 6 am and 8 am but then increased to over 600 µg/m³ during the daytime, affirming the concentrations of PMs followed occupancy patterns. The magnitude of PMs was higher in B01 due to lack of ventilation, as compared to P06 and B07 with higher frequency of window opening.

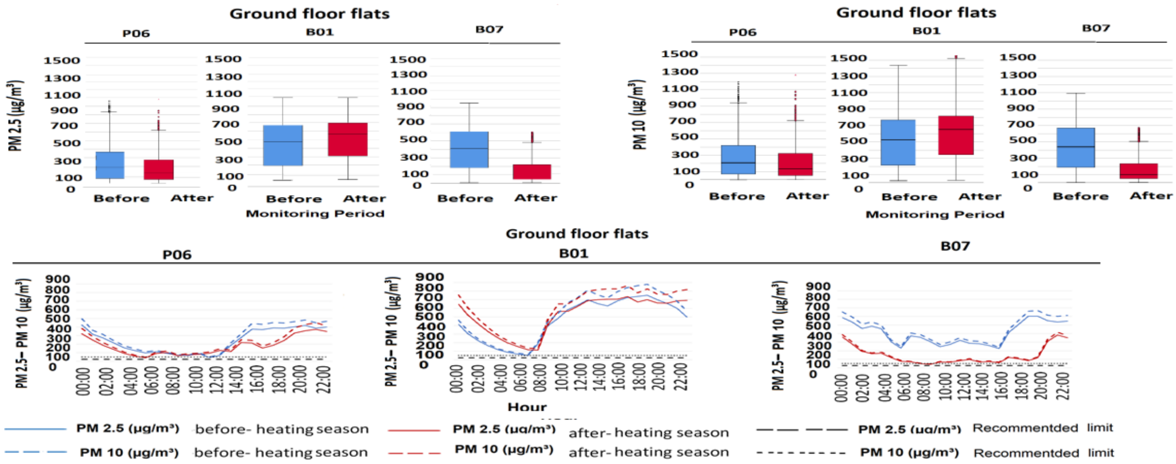

Figure 3. Distribution of $PM_{2.5}$ and PM_{10} (top) and mean daily profiles (bottom) across three ground floor flats with highest ranges of pollutants in heating season

Volatile organic compounds (VOCs: ethanol (EtOH) and isobutylene)

There was strong association identified between the two VOCs, ethanol (EtOH) and isobutylene, across all five case study flats with Spearman correlation of 0.8 (significant at 0.001). While the levels of EtOH and isobutylene were low in B05 and B07, they were found to be higher in P03 and P06 pre-heat pump reaching to means of 4 ppm and 0.4 ppm respectively. Although pre-retrofit ethanol and isobutylene reached to the peaks of 8 ppm and 0.8 ppm in P06 and 9 ppm and 0.9 ppm in B07 respectively, the level of VOCs reduced to nearly zero across the four flats post-retrofit, possibly due to the increase in the frequency of window opening. Despite no recommended limits for EtOH and isobutylene concentrations in domestic buildings, flat B01 experienced maximum level of EtOH and isobutylene that could be monitored by Airthinx device (10 ppm and 1 ppm respectively) pre and post-retrofit. This was likely to be due to the consistent use of air fresheners by the resident to eliminate stale cigarette smoke, which confounded by the lack of opening windows.

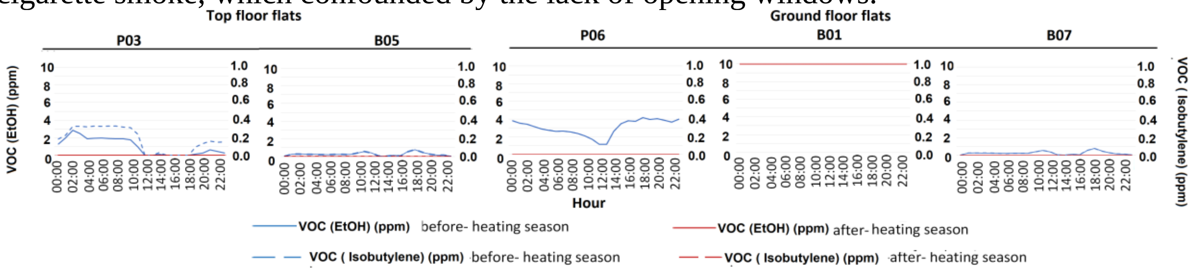

Figure 4. Mean daily profiles of EtOH and isobutylene across five flats in heating season

Formaldehyde levels

Formaldehyde levels were measured to be below the WHO recommended level of 0.1 mg/m^3 (30-min average) (CIBSE, 2020) in four flats, with mean being below 0.01 mg/m^3 pre- and post-retrofit (Figure 5). In contrast, the level of formaldehyde was significantly high in flat B01 in both periods with mean level as high as 0.2 mg/m^3 due to high exposure to tobacco smoke and limited window opening. Despite low level of formaldehyde, various spikes were identified across the flats during the monitored period, possibly due to the residents' use of cleaning products and cosmetics. The spikes were especially high in flat B01 rising during the latter half of the day when the resident was awake and possibly smoking.

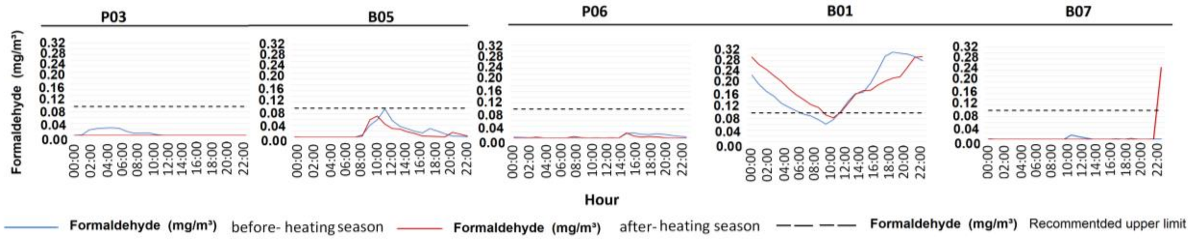

Figure 5. Mean daily profiles of formaldehyde across five flats in heating season

Relationship between pollutants

Statistical analysis was undertaken to explore any relationship between indoor pollutants. In the ground floor flats P06 and B07, regression analysis showed moderate correlation (R^2=0.39, R^2=0.56) between VOC (ethanol) and CO_2, and strong correlation (R^2=0.91, R^2=0.62) between VOC (ethanol) and $PM_{2.5}$ before retrofit as shown in Figure 6 below. Since EtOH and Isobutylene, and $PM_{2.5}$ and PM_{10} had similar association with other pollutants, PM_{10} and Isobutylene have been excluded from Figure 6. After installation of heat pumps, these correlations became weak possibly due to the increased frequency of window opening in flats P06 and B07. In the ground floor flat B01 with limited window opening, weak correlation (R^2=0.3) was identified between formaldehyde and PMs pre- and post-heat pump.

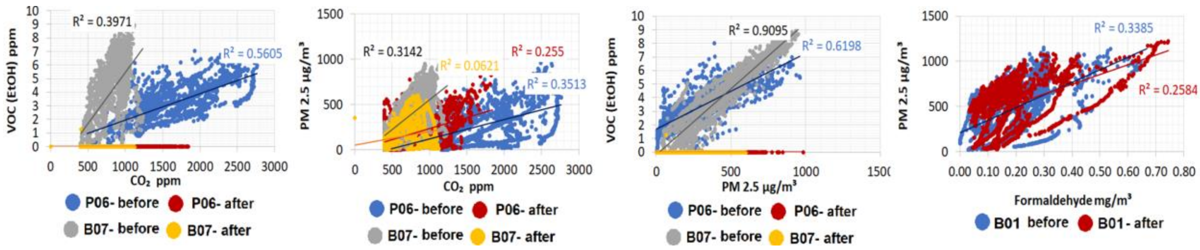

Figure 6. Scatter plots showing relationship between VOC, CO_2, $PM_{2.5}$ in flats P06 and B07, and $PM_{2.5}$ and formaldehyde in Flat B01 with considerable associations

Mean daily profiles of CO_2 and $PM_{2.5}$ in P06 and B07 pre and post-heat pump showed despite reductions in CO_2 and $PM_{2.5}$ levels after retrofit, the pollutants followed similar patterns throughout the day (Figure 7). CO_2 and $PM_{2.5}$ concentrations saw similar changes in peaks and troughs in both periods, rising from 12 pm until midnight, and reducing from mid-night until morning when the living rooms were unoccupied. This indicated that levels of CO_2 and PMs were affected by the presence of residents.

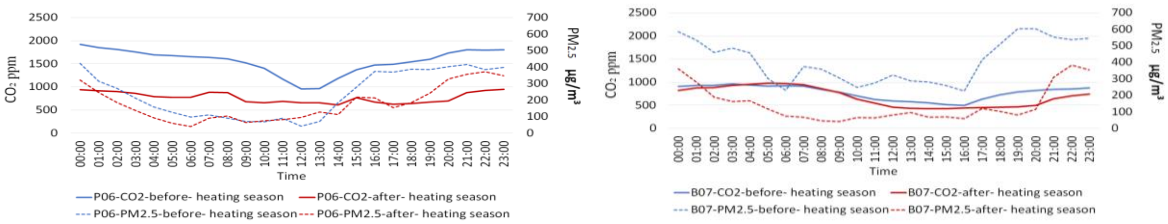

Figure 7. Mean daily profiles of $PM_{2.5}$ and CO_2 in ground floor flats P06 (left) and B07 (right)

5 DISCUSSION

The study has empirically revealed the diversity in the magnitude and daily pattern of indoor pollutants observed in a small sample of social housing flats before and after low carbon heat pump installation, despite having similar construction, location and occupancy. There was a stark difference found in concentrations of indoor pollutants in flats that opened windows frequently versus those that did not. Post heat pump installation, since heating was left always on and was cheaper to run, majority of residents were found to open windows more often as compared to keeping windows closed to conserve heat from the more expensive to run night storage heaters. This change in frequency of window opening led to increase in indoor-outdoor exchange thereby improving indoor air quality. This increase in window opening also led to a fall in CO_2 levels to below 900 ppm in the majority of monitored flats.

Occupants' activities such as smoking were found to be closely related to the prevalence of $PM_{2.5}$ and PM_{10}, as well as VOCs ethanol and Isobutylene. In flat B07 with a heavy smoking resident, the levels of $PM_{2.5}$ and $PM_{10,}$ which can cause lung and heart disease, remained above the recommended upper limits (>25 μg/m³ and >50 μg/m³ respectively) post-heat pump despite frequent window opening habit of the resident. This exposes the need for integrating continuous background ventilation that could be demand controlled, such as trickle vents opening further as the levels of these pollutants rise. This is vital in homes with low temperature heat pumps that could quickly lose heat with purge ventilation. On the other hand, the level of VOCs across the majority of flats reduced (Except flat B01) post-heat pump due to increased ventilation. However, flat B01 with limited window opening experienced the highest levels of VOCs and formaldehyde due to the continuous use of air fresheners to reduce stale tobacco smoke. High levels of these pollutants can cause burning sensation in eyes, nose and throat, coughing, wheezing nausea and skin irritation. The high concentration of indoor air pollutants that associated with occupants activities indicates an urgent need for raising residents' awareness on avoiding smoking inside homes and instead ventilating homes adequately.

Given the diversity in the concentrations of different indoor pollutants observed across the flats, it is vital to consider IAQ parameters beyond temperature and RH, while upgrading dwellings with low carbon heating systems and building fabric upgrades, since indoor-outdoor air exchange may be affected post-retrofit. Smart sensors could be integrated with heat pump sensors to continuously record different IAQ parameters in relation to use of heating. Smart ventilation strategies (such as demand controlled ventilation) could be integrated that increase indoor-outdoor air exchange when a rise in indoor pollutants is detected. The data gathered can also be used to provide feedback to residents to help them change their own behaviours to manage indoor pollutants. Low-cost IAQ monitors have a role to play here but it is important to keep in mind that such devices may underestimate the concentration of some indoor air pollutants such as formaldehyde (Goletto et. al, 2020). They may also react to other harmless indoor gases giving false detection.

One limitation of this study is the small sample size although the findings show trends that may be representative of social housing dwellings. Moreover air change rate was not measured but calculated using the Reduced Data Standard Assessment Procedure (RdASP) methodology for this study.

6 CONCLUSIONS

This stud has undertaken empirical measurement of IAQ before and after smart heat pump retrofit in five naturally-ventilated social housing flats in Oxford. Plug-in Airthinx sensors monitored IAQ parameters including CO_2, Particulate Matters (PM2.5, PM10), formaldehyde (CH_2O) and Volatile Organic Compounds (VOCs: ethanol and Isobutylene), temperature and relative humidity (RH) in the living rooms of all flats during the heating season, for one week before and one week after heat pump installation. Overall the levels of majority of indoor pollutants including CO_2 were found to fall in dwellings possibly due to increased window opening as a resul of having a cheaper, always-on heat pump based heating system. Across four flats, formaldehyde levels were found to be less than recommended limit of 0.1 mg/m³, although in Flat B01, mean daily levels of formaldehyde exceeded 0.1 mg/m³ due to the use of air fresheners to tackle stale cigarette smoke. In three flats with tobacco smokers, PMs levels were found to be higher than the recommended guidance - with $PM_{2.5}$>25 μg/m³ and PM_{10}>50 μg/m³ in both periods due to high exposure to pollutants associated with cigarette smoke despite an increase in natural ventilation, indicating the need to have some form of continuous background ventilation. Levels of VOCs showed reductions in flats that opened windows frequently post-heat pump. The study also showed the association between indoor pollutants and occupancy patterns and behaviour implying a need to raise occupants' awareness about the health effects of indoor pollutants, and how their concentrations could be reduced through natural ventilation.

It is vital that monitoring and control of indoor pollutants is integrated alongside the design and delivery of energy retrofit measures (heating, building fabric) in UK homes that will remain to be largely naturally ventilated. This will ensure that energy retrofits lead to a reduction in energy use as well as improved indoor air quality in homes.

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