Indoor Environment and Energy Use in Existing and Retrofitted Social Housing Dwellings: Insights from BPE (POE) Studies

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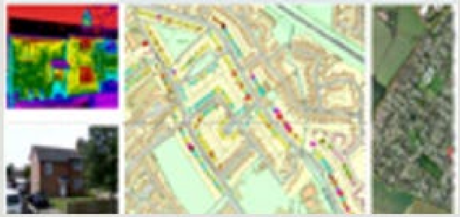
Outline of presentation

- About us
- Background and context
- **Research project 1** (building fabric upgrade) – IAQ assessment in a deep energy retrofit of a block of flats
- **Research project 2** (heating system upgrade) – IAQ assessment in flats with ground source heat pumps
- **Research project 3** (existing dwellings) – IAQ assessment in existing houses prior to whole-house energy retrofits
- Final thoughts/Future directions

About us

Low Carbon Building Research Group,
Oxford Institute for Sustainable Development



CARBON COUNTING AND CARBON MAPPING

Urban/Community scale topographical carbon analysis

ADVANCED LOW CARBON REFURBISHMENT

Whole house deep retrofit to achieve more than 70% reduction in emissions

BUILDING PERFORMANCE FEEDBACK AND POST-OCCUPANCY EVALUATION

Evaluating & fine-tuning buildings to meet targets

Empirical assessment of IAQ in dwellings which are:

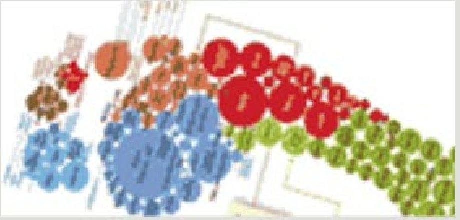
- New build
- Existing
- Retrofitted

EVALUATING LOW CARBON COMMUNITIES

Assessing the impact and limitations of community led low carbon initiatives

CLIMATE CHANGE ADAPTATION OF BUILDINGS AND NEIGHBOURHOODS

Future proofing buildings



GLOBAL COMMON CARBON METRICS

Developing a universal method of measuring a building's carbon footprint

https://www.brookes.ac.uk/architecture/research/low-carbon-building-group/

Gap between design intent and actual outcome: Performance Gap

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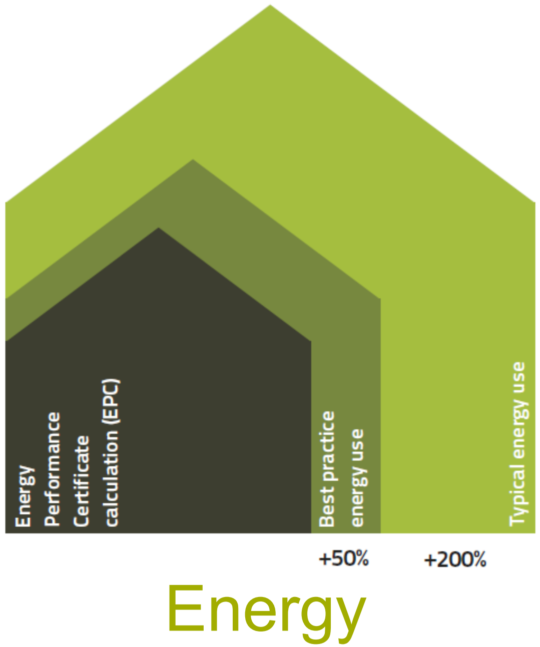
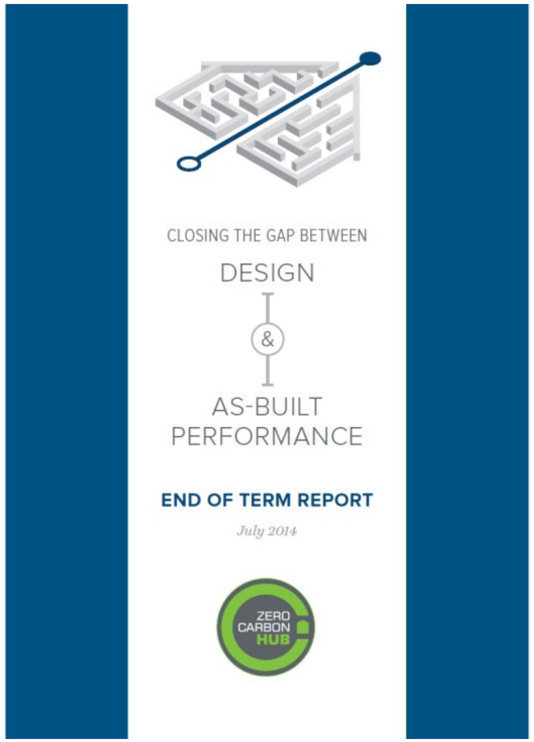
- Even the **best** (low/zero carbon) buildings fail to perform as anticipated due to assumptions made in modelling, build process and quality, systems integration and commissioning, handover and operation, and crucially the understanding, comfort and motivation of occupants.

- Widespread presence of such a gap
  - Could undermine net zero targets
  - Higher energy bills for owners and occupants
  - Fallout from underperforming new homes could be damaging to reputation and business.

- Building performance evaluation (BPE) studies provides a means to identify the gap and its likely causes, fine-tune performance and informing future building design, specification.





Scope of BPE studies: socio-technical approach

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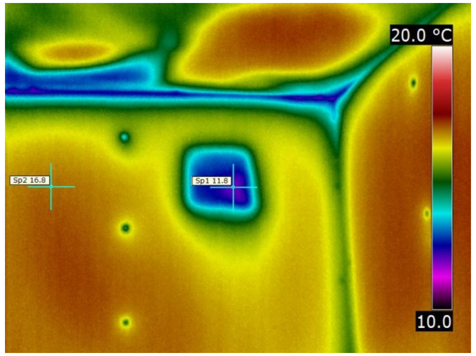
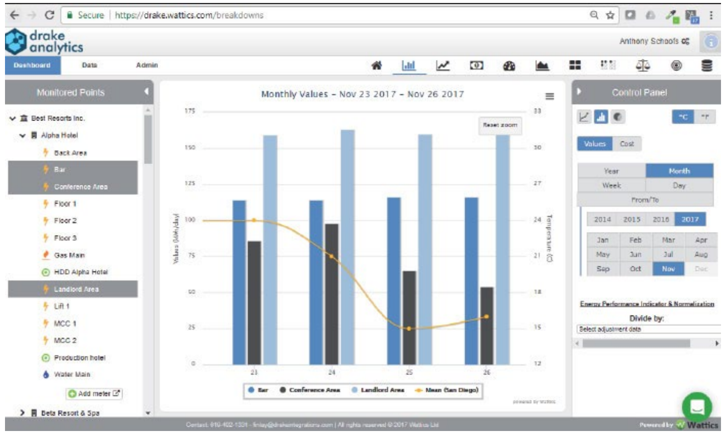
As-built performance: compare as-built performance with design intent.

- Review of design intent
- Building fabric performance testing
- System performance testing / commissioning review
- Communication of design intent (handover)

In-use performance: compare operational performance with design intent

- Energy use, energy end use monitoring
- System performance (e.g. heating system, ventilation system)
- Environmental monitoring: Indoor Air Quality
- Occupant experience/behaviours





BPE studies of low/zero carbon buildings

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CODE LEVEL 5 HOMES IN SWINDON

DOMESTIC IN-USE

CODE LEVEL 5 HOMES IN SWINDON

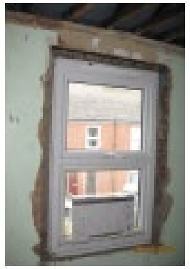
DOMESTIC POST COMPLETION & EARLY OCCUPATION

CODE LEVEL 4 HOMES IN BICESTER

DOMESTIC IN-USE

THAMES VALLEY HOUSING

DOMESTIC IN-USE



PROJECT TYPE: *Before and after retrofit* BPE study

DURATION: 2009-2013

NUMBER OF DWELLINGS STUDIED: One ($78m^2$)

FUNDED BY: Innovate UK's *Retrofit for the Future* competition

PARTNERS: Ridge & Partners LLP; Oxford City Council

FUNDING: £150,000

PROJECT TYPE: *Before and after retrofit* BPE study

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NUMBER OF DWELLINGS STUDIED: One

FUNDED BY: Innovate UK's *Retrofit for the Future* competition

PARTNERS: Penoyre & Prasad LLP; XCO2 Energy; Lakehouse Contracts Ltd; Osborne Edwards; East Thames Group

FUNDING: £150,000

Funded by: Innovate UK Building Performance Evaluation programme

BPE state of the nation: measuring building performance at scale

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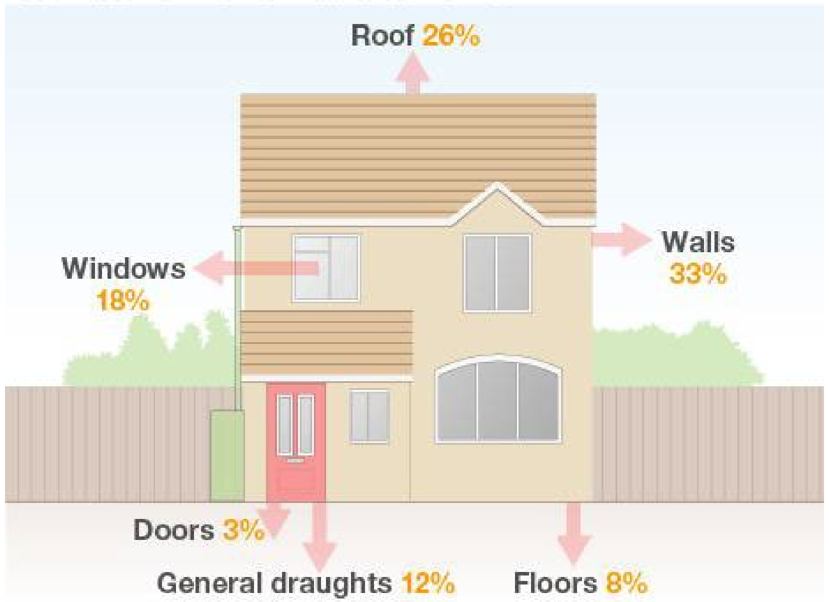
https://building-performance.network/wp-content/uploads/2020/06/State-of-the-nation-report-June-release-FINAL-UPDATED.pdf

Background and context

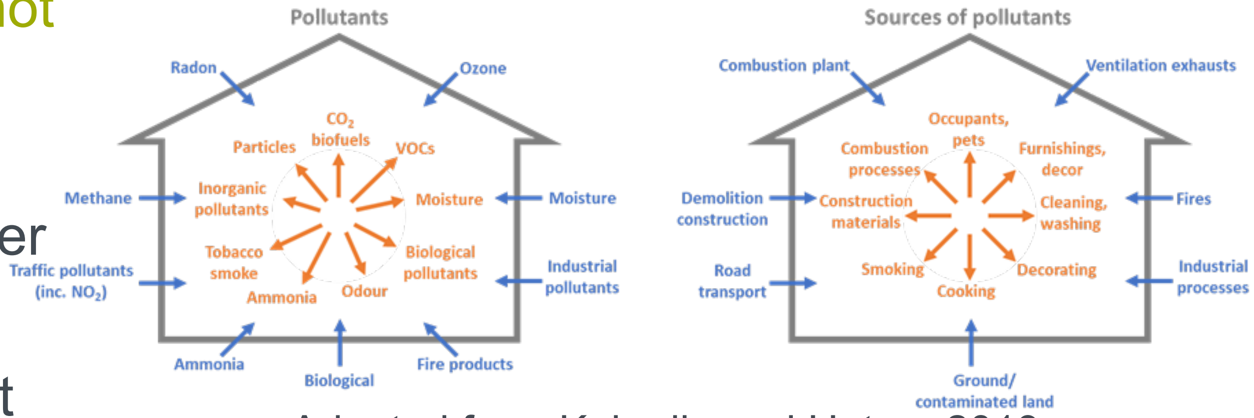
Background and context

- To reduce heating demand, retrofit measures increase airtightness, thereby reducing infiltration of outdoor pollutants which also reduces removal of indoor pollutants.
- We spend up to 90% of time inside our homes and buildings. UK housing stock varies in terms of age, construction materials, dwelling form, occupancy all of which effect the indoor environment.
- More attention needs to be paid to ensure that conditions inside our homes and buildings do not cause negative health outcomes.
- In the UK, there is limited empirical data to quantify indoor pollutants and how they vary over time, and by building to building.
- There is also limited empirical data on the effect of home energy retrofits on indoor air quality.



Heat loss in a typical uninsulated dwelling

Source: Energy Saving Trust



Adapted from Kukadia and Upton, 2019

Report on Indoor Air Quality

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AIR QUALITY EXPERT GROUP

Indoor Air Quality

Prepared for:

Department for Environment, Food and Rural Affairs;
Scottish Government; Welsh Government;
and Department of Agriculture, Environment and Rural Affairs in Northern Ireland

Membership

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National Centre for Atmospheric Science, University of York

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National Centre for Atmospheric Science, University of Manchester

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Emeritus Professor Claire Reeves
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Professor Nicola Carslaw
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Dr Andy Dengel
BRE Environment

Professor Sani Dimitroulopoulou
UK Health Security Agency

Professor Rajat Gupta
Oxford Brookes University

Regulations in the UK; high VOC content products such as paints have been regulated through EU Directives, and numerous labelling schemes exist for construction products across Europe, but not in the UK. Less well defined are standards for acceptable concentrations of air pollutant indoors. Advisory health-based guideline values on selected indoor air pollutants issued by WHO and UKHSA (formerly PHE) do not have any statutory underpinning. In the workplace there are limits on occupational exposure to a range of airborne chemicals. These assume that the time spent in these settings is limited and those exposed are healthy adults, so they are set at high time-weighted concentrations. Occupational indoor air quality standards are likely not appropriate for a wider population that includes children, elderly and vulnerable individuals.

A major area of uncertainty identified relates to current concentrations of indoor air pollution in UK homes and their trends over time. Most AQEG reports on outdoor air quality can draw on extensive observational data collected through national, local authority and research networks, on many different pollutants, and often over multi-decadal periods. No such datasets exists for indoor air quality in the UK. Instead, the only quantitative evidence on indoor air quality comes from individual research studies in specific indoor micro-environments (e.g., homes, schools, transport, rail stations, shops etc.) with fragmented and inconsistent pollutant speciation. Most research studies report information for only a small number of pollutants over a short period of sampling, providing only a snapshot of concentrations and with limited data on occupant activities.

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Project Tcosy2:

Deep energy retrofit of a block of flats

Study context

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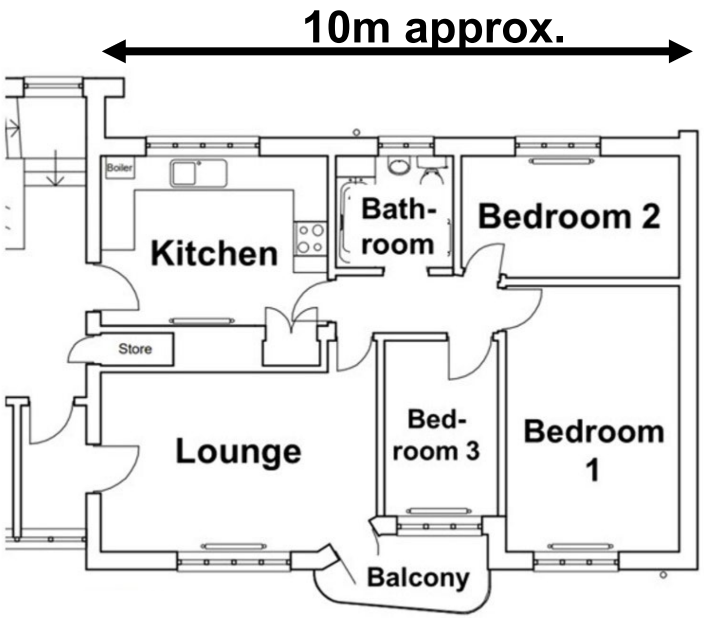
- Deep energy retrofit project - Fabric-focussed deep retrofit on low-rise block of 6 flats (occupants in-situ throughout).
- Funded by BEIS thermal efficiency innovation fund, 2018 – 2021, £1.2 million. Project partners: Beattie Passiv, Enhabit, Oxford Brookes University
- Full wrap-around external insulation of the building fabric, triple-glazed windows and mechanical ventilation with MVHR installed in each flat.
- EnerPHit retrofit standard:
  - Space heating demand of **25 kWh/m^{2}annum**;
  - Air tightness **<1 ach^{-1}@50Pa**.
  - U-value: overall design target **0.15 Wm^{-2}K**
- Longitudinal monitoring of IAQ (including formaldehyde, VOCs and PM's) during the post-retrofit period.
- Influence of occupant behaviour on indoor air quality.



Typical floorplan of flats

Overview of the case study flats

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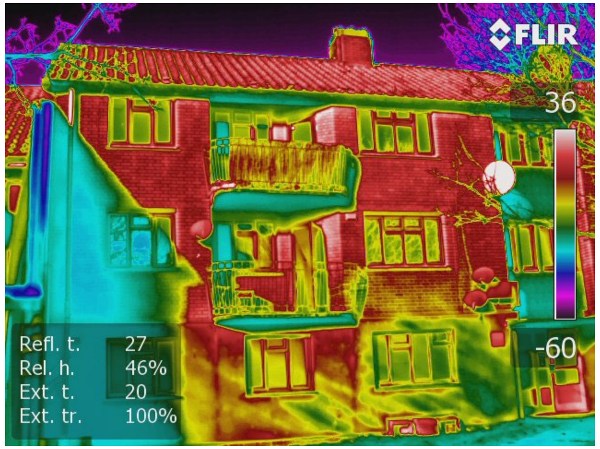
	A (ground)	B (middle)	C (top)	D (ground)	E (middle)	F (top)
Occupants	1 working adult (+1 adult 2 weeks/ month)	1 working adult, 3 school-aged children	1 not working adult, 3 school-aged children	2 retired/not working adults, 1 working adult, 1 infant	1 working adult, 2 school-aged children	2 retired adults
Occupied	Evenings only	All day	All day	All day	Afternoons and evenings	All day
Pets	3 cats	1 dog	1 dog	1 cat	1 dog	>20 including 7 cats
Smokers	No	Yes	Yes	Yes	No	No
Hob extractor	Yes	No	No	No	No	No
Laundry	2-3 loads/week, tumble drier	7 loads/week, tumble drier	7 loads/week, tumble drier	7 loads/week, hang inside	2-3 loads/week, hang on balcony or inside	4 loads/week, hang on balcony or inside
Experienced condensation/ mould	Yes (bedrooms)	Yes (throughout)	Yes (throughout)	Yes (bathroom)	No	Yes (hallway and lobby)

BPE methods (before/after retrofit)

- **Building fabric:**
  - Air-tightness test
  - Thermographic survey
  - U-value test



- **Energy performance:**
  - Gas and electricity monitoring

- **Environmental monitoring:**
  - Monitoring of indoor temperature, relative humidity, CO_2 levels, and indoor air pollutants (TVOCs, PM) at 15’ frequency.
  - Monitoring from Oct’ 2020 (1 flat) and May 2021 (3 flats) until Dec’ 2021.

- **Occupant feedback**
  - Occupancy patterns and behaviours which influenced indoor environment and energy consumption.

Retrofit results

- *Pre-retrofit* - low temperatures and high humidity leading to damp/mould throughout.
- Retrofit conducted Oct’ 2019 to Dec’ 2020.
- Air-tightness went from **3.2 ach^{-1}@50Pa** (pre-retrofit) to **0.67 ach^{-1}@50Pa** (post-retrofit).
- Gas use (for heating) hugely reduced - gas supplier contacted occupant to ask why.
- *Post-retrofit*- Occupants described warmer, more stable temperatures and elimination of damp and mould.

Indoor temperature: before/after retrofit

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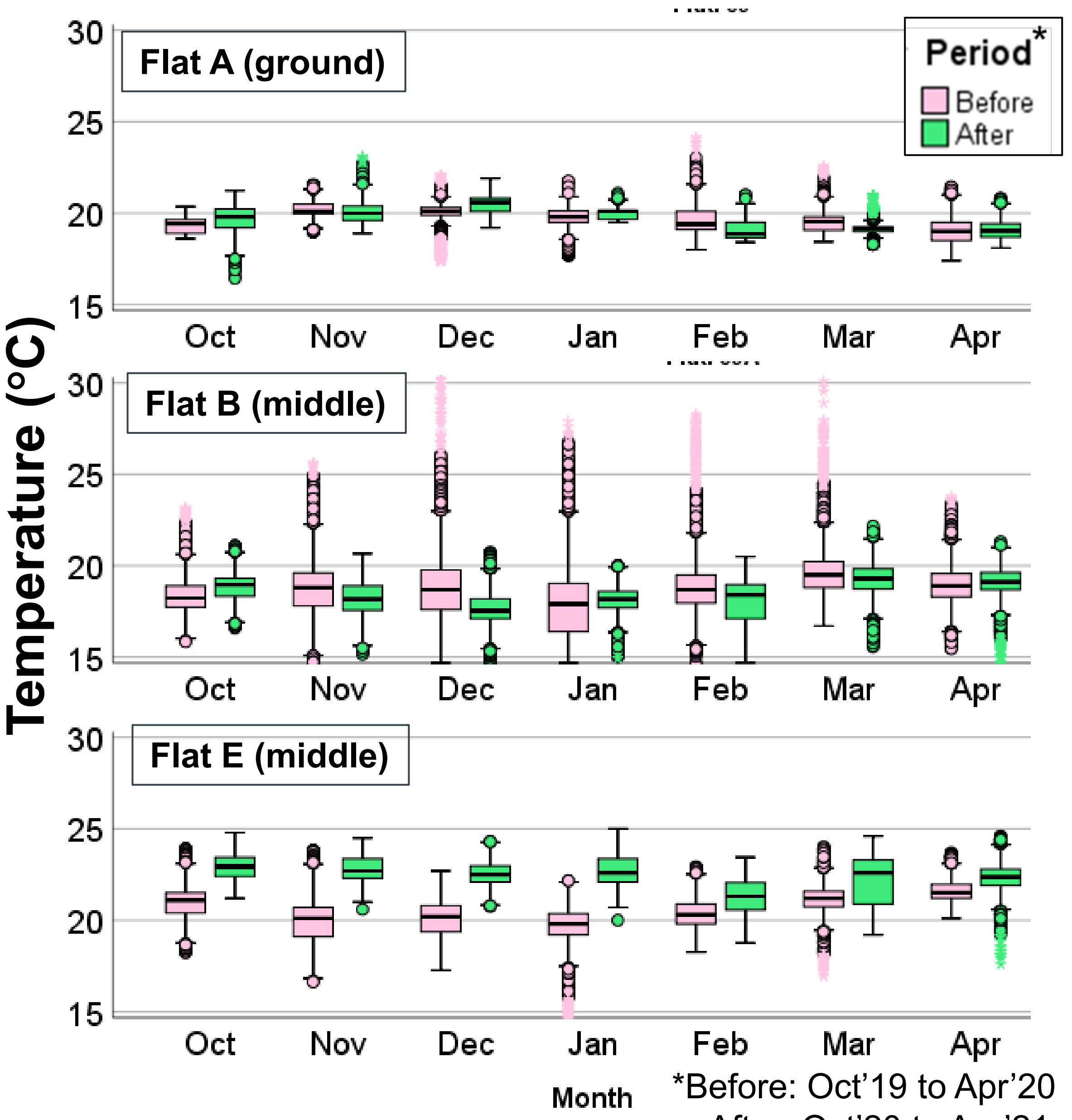
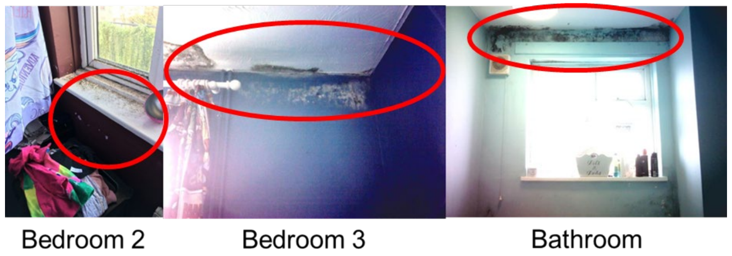
- Post-retrofit temperatures tended to have **narrower interquartile ranges (more stable)**, and less extreme high and low temperatures.
- Ground floor flat A temperatures were much more stable and relatively unchanged post-retrofit.
- On the middle floor, flat B's temperatures were slightly cooler, but E's were slightly warmer post-retrofit.



*Before: Oct'19 to Apr'20
After: Oct'20 to Apr'21

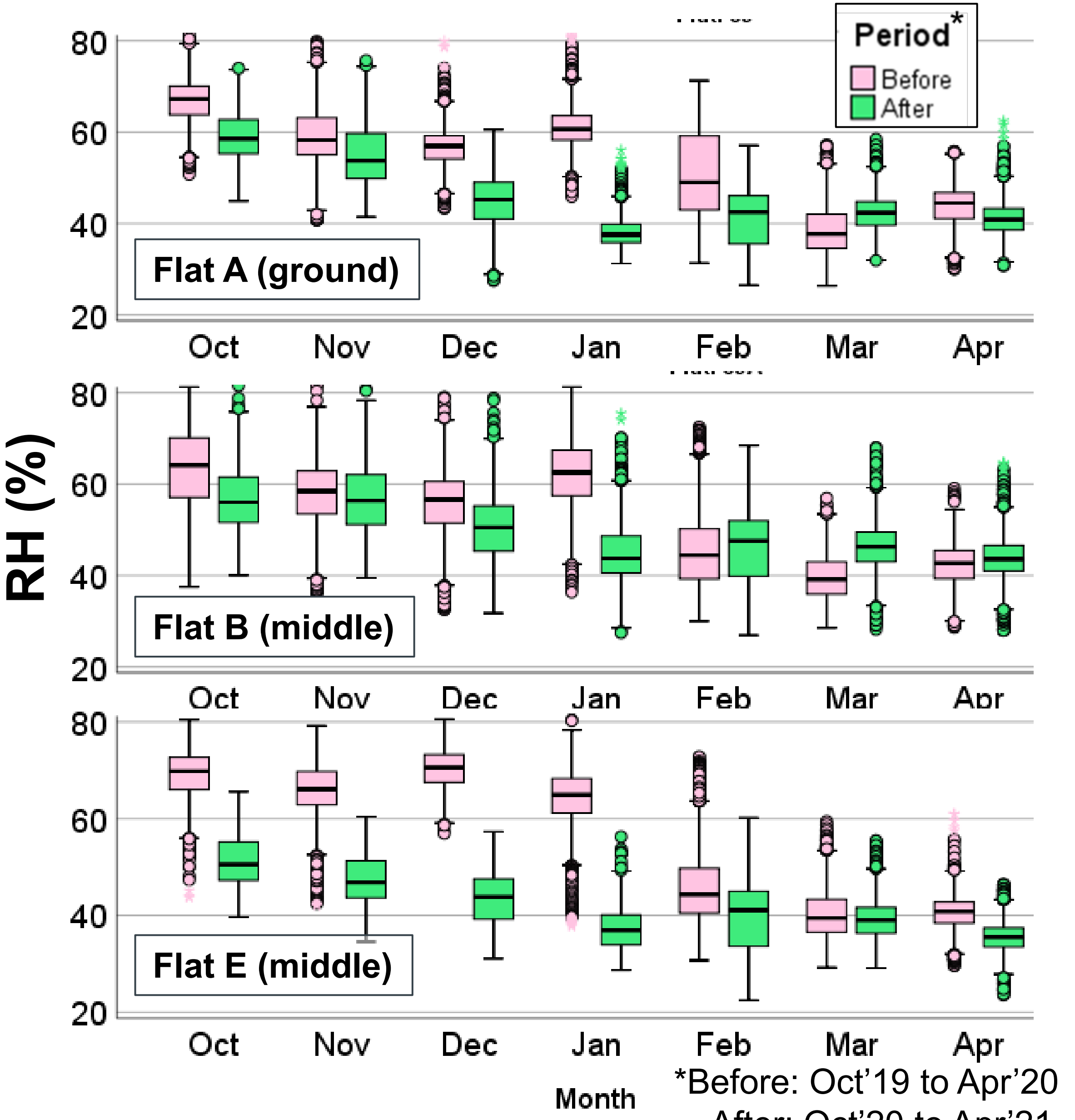
Relative humidity: before/after retrofit

Pre-retrofit mould in flat C (top floor)



- Pre-retrofit RH levels were often in the 60-80% range, with damp and mould prevalent in several flats.

- After commissioning of MVHR in Feb'20 (flats B and E) and Mar'20 (flat A), RH fell significantly sometimes going below 40%.



*Before: Oct'19 to Apr'20
After: Oct'20 to Apr'21

Indoor CO_2 levels: before/after retrofit

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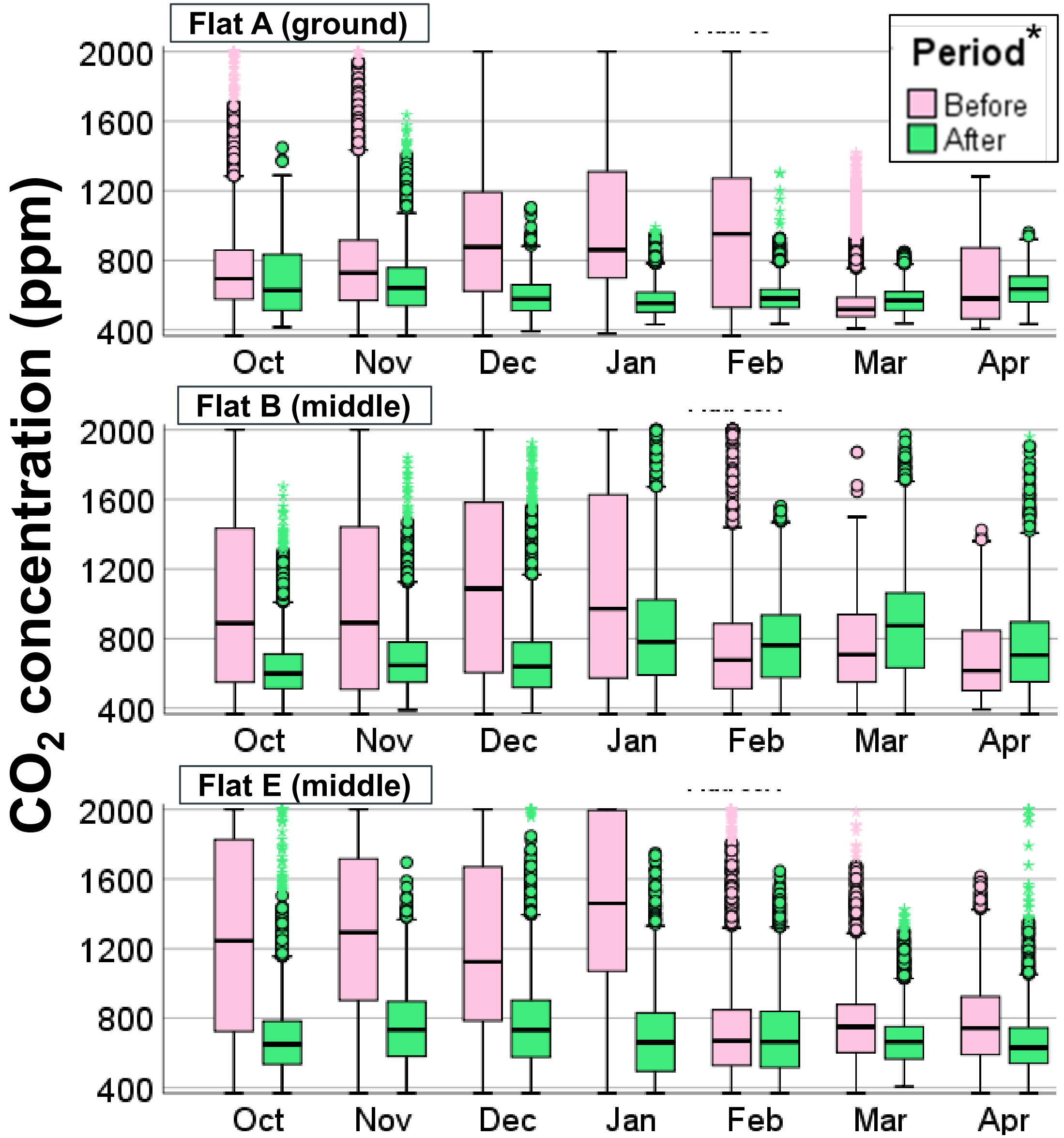
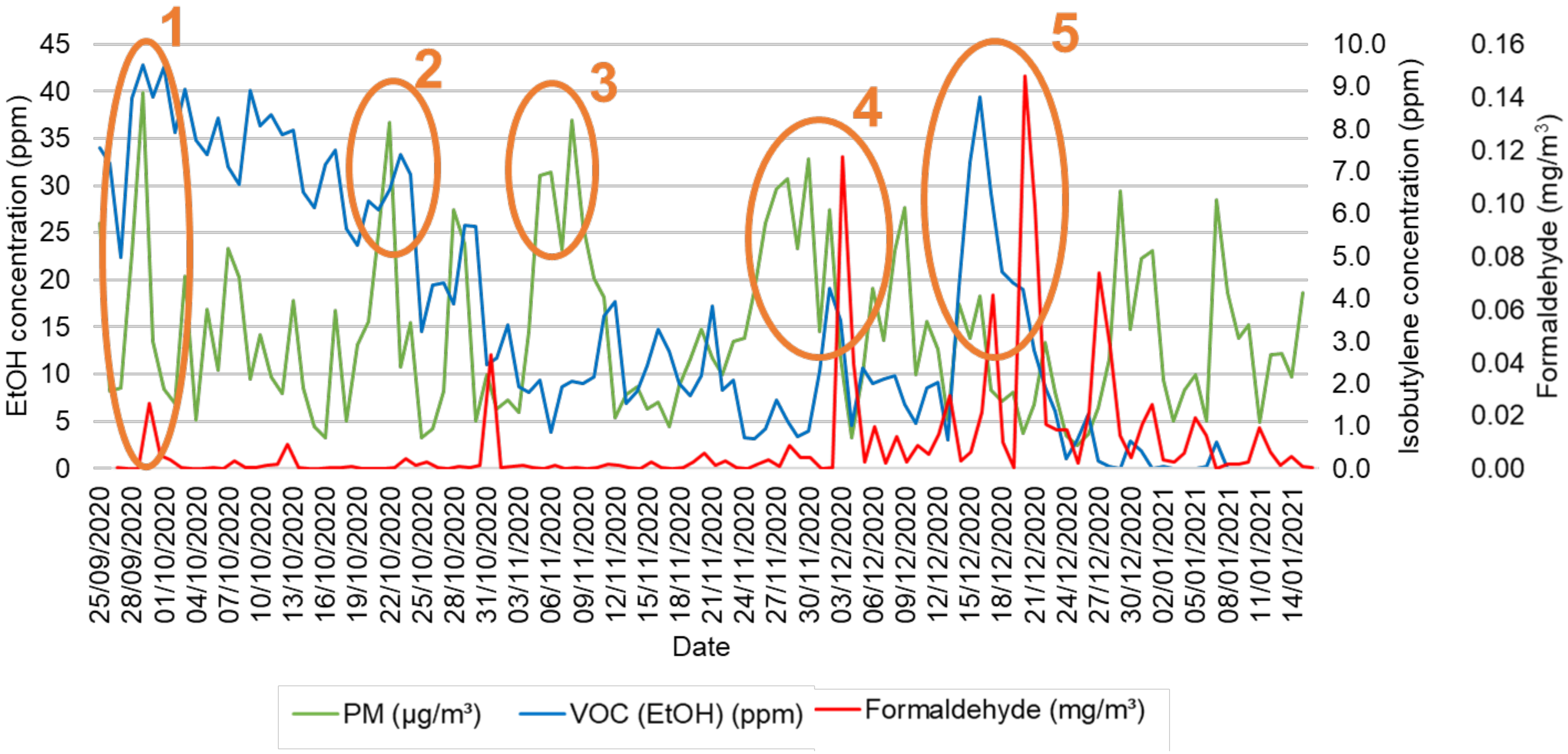
- MVHR commissioned in Feb'20 (flats B and E) and Mar'20 (flat A).
- After commissioning, CO_2 much lower, although peaks still above 2000 ppm occasionally.
- Flat A's lower occupancy meant generally lower CO_2 levels.



*Before: Oct'19 to Apr'20
After: Oct'20 to Apr'21

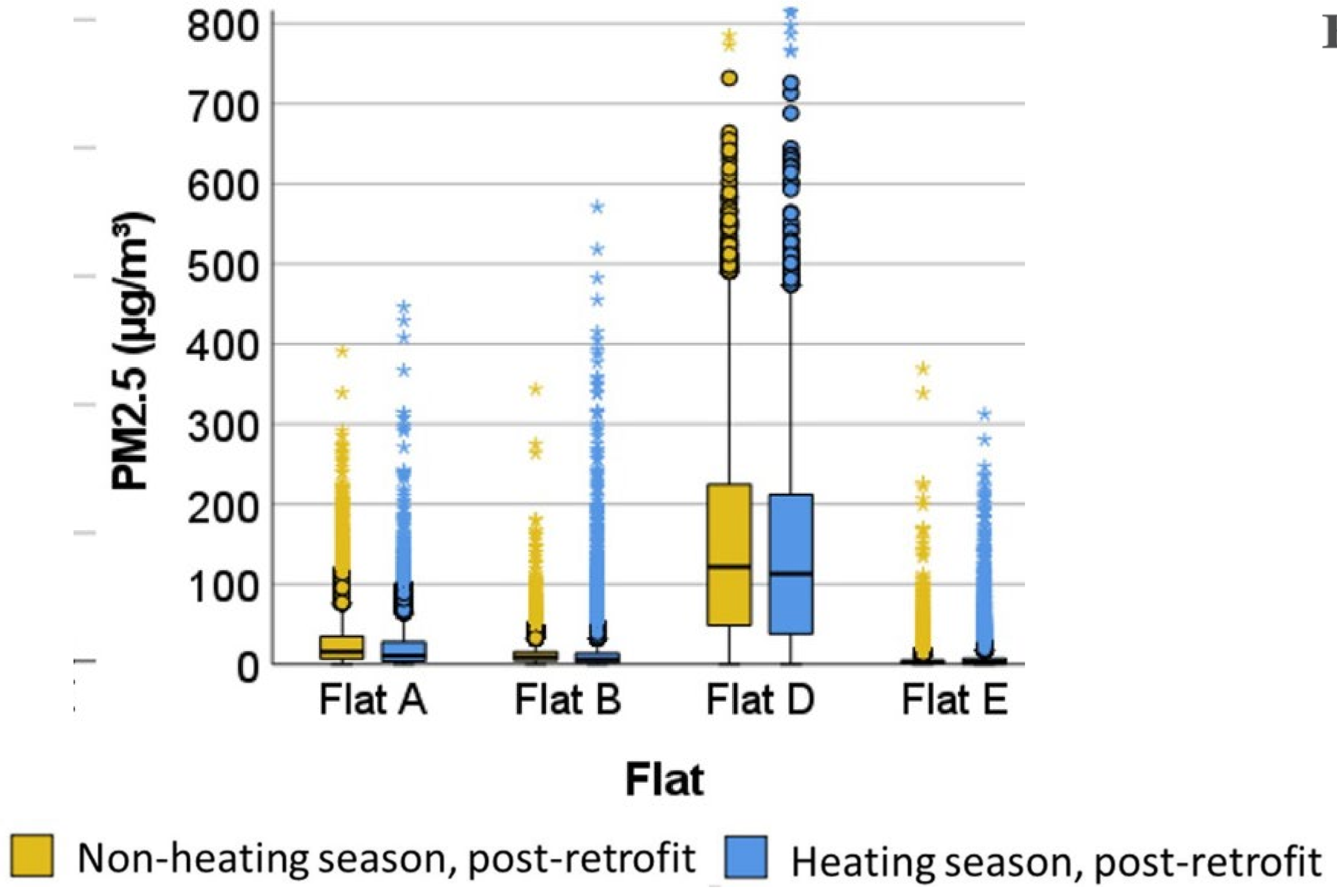
IAQ: during/after retrofit

- IAQ parameters monitored in Flat E
- Spikes in levels corresponded to specific retrofit works:
- (1) Installation of windows, internal remedial decoration.
- (2) External balconies installed, remedial decoration.
- (3) MV installed and commissioned for hallway.
- (4) Ventilation installed in hallways.
- (5) Removal of scaffolding, front access door installed.



- Ongoing IAQ monitoring shows indoor pollutant levels continuing to fall over time.

Post-retrofit: PMs



- **PM_{10} and $PM_{2.5}$** levels in flats A, B and E significantly lower than in flat D.
- Flat D exceeded 45 μg/m^3 (PM_{10}) almost every day due to occupants' personal activities such as smoking and use of air fresheners were found to be closely related to the prevalence of $PM_{2.5}$

Occupant feedback: pre/post-retrofit

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Pre-retrofit	Post-retrofit
• Residents complained about damp and mould issues. • Residents felt cold in winter. • They complained about the cost of heating. • "The kitchen gets too warm, but the lounge gets too cold" (flat E). • "The small bedroom gets really cold" (flat A). • "The main bedroom gets cold in winter" (flat A). • "The main bedroom gets so cold we have to sleep in the back bedroom". (flat F).	• Residents were pleased with the flats feeling warmer. • "The heating stays in the flat now so we save money" (flat D). • "We're not getting headaches like we used to if the windows were shut too much because we've got the constant air in" (flat F). • However, residents had concerns about the finish of the retrofit, especially inside the flats. • They were also displeased with the retrofit time-scale and disruption caused (Covid restrictions also caused delays).

Project EnergyREV

Retrofitting heat pumps and smart controls

Study objectives and methods

- Empirically examine changes in indoor air pollutants before and after heat pump installation in five co-located social housing flats in Oxford.
- Part of EPSRC funded EnergyREV programme.
- Covering one week pre- and one week post-heat pump installation from Oct 2020 to Apr 2021 (heating season).
- Mixed-methods approach:
  - **Household survey** covering socio-demographics, resident heating and ventilation behaviours.
  - **Physical characteristics** drawn from Energy Performance Certificates (EPC).
  - **Monitoring IAQ parameters:** using Airthinx monitoring device, measured VOCs (EtOH and Isobutylene), PM2.5, PM10, CO_2, formaldehyde (CH_2O), temperature and relative humidity (RH) with 5' interval. Data transmission through the Cloud.

Case study flats: characteristics

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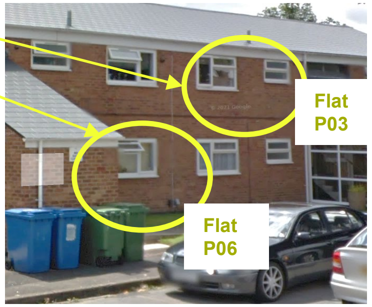
- Two top floor and three ground floor flats in a housing estate located in a socially-deprived area in Oxford, UK.
- Energy rating of C (pre-heat pumps).
- Cavity wall insulation installed in flats P03 and P06 to improve energy efficiency.
- All flats naturally ventilated through window opening.



Flats	Characteristic	Top floor flats		Ground floor flats		
		B05	P03	B01	B07	P06
	Energy efficiency rating	C	C	C	C	C
	Environmental impact rating	D	D	D	D	D
	Flats floor area (m²)	33	47	33	61	47
	Building fabric insulation	Filled cavity wall that improved in P03 and P06				
	Glazing	Double glazed				

Household characteristics

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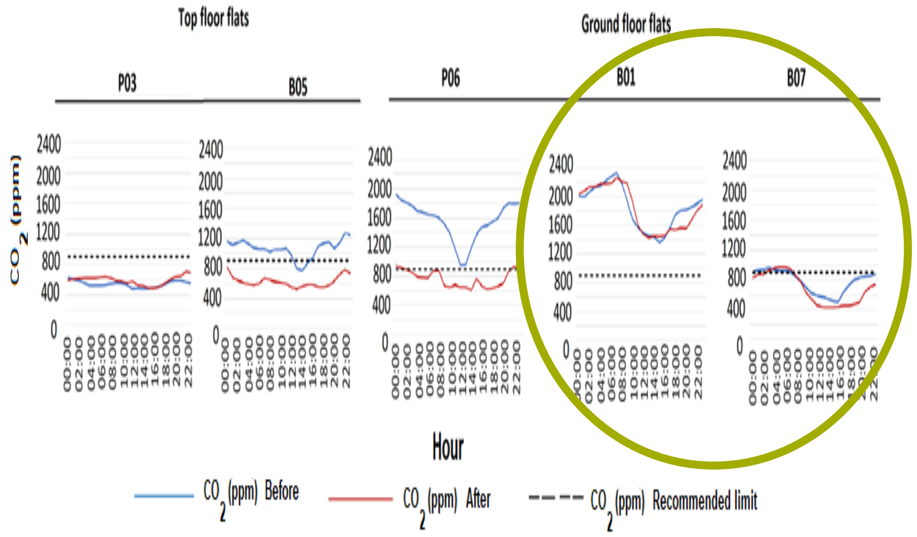
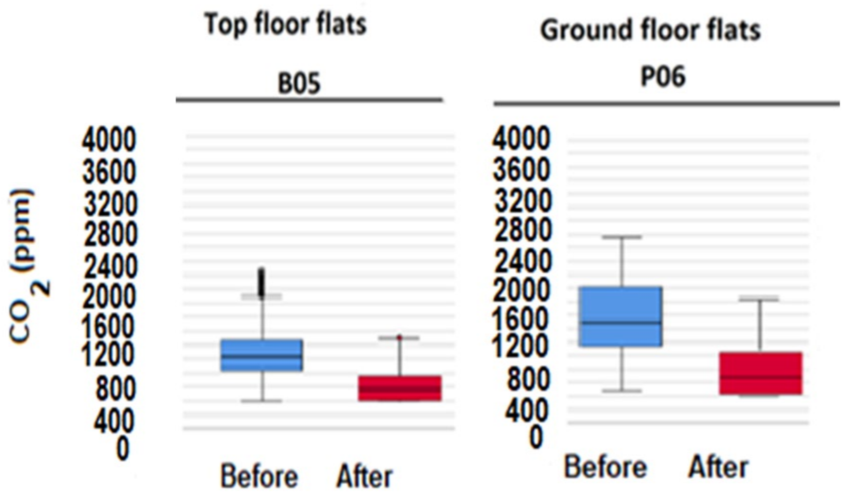
- All case study flats had single occupancy.
- Residents aged between 41 to 70 years.
- Flats occupied continuously either most or all of the time.

Households	Characteristic	Top floor flats		Ground floor flats		
		B05	P03	B01	B07	P06
	Number of occupants	1	1	1	1	1
	Age (years)	50	41	63	70	57
	Weekday occupancy	Most of the time	Most of the time	24/7	24/7	Most of the time
	Weekend occupancy	24/7	Morning	24/7	24/7	24/7
	Employment status	Employed	Employed	Retired	Retired	Employed

CO_2 levels

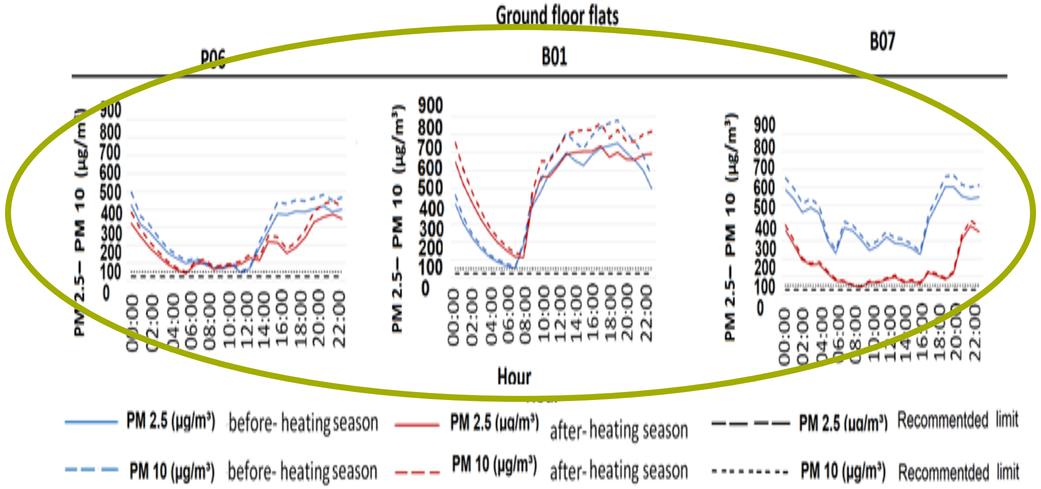
- CO_2 levels were found to be reduced across majority of flats after heat pump installation.
- Increase in frequency of window opening, since heat pump based system was always-on but cheaper, as compared to electric storage heaters.
- Occurrence of peaks and troughs in CO_2 levels did not change post-heat pump possibly since occupancy patterns remained same.
- Flats P06 and B05 experienced significant reductions in CO_2 with mean less than 900 ppm.
- Mean CO_2 levels measured **below 900 ppm in both periods in flat B07** due to regular window opening, **in contrast to flat B01** that opened windows infrequently.

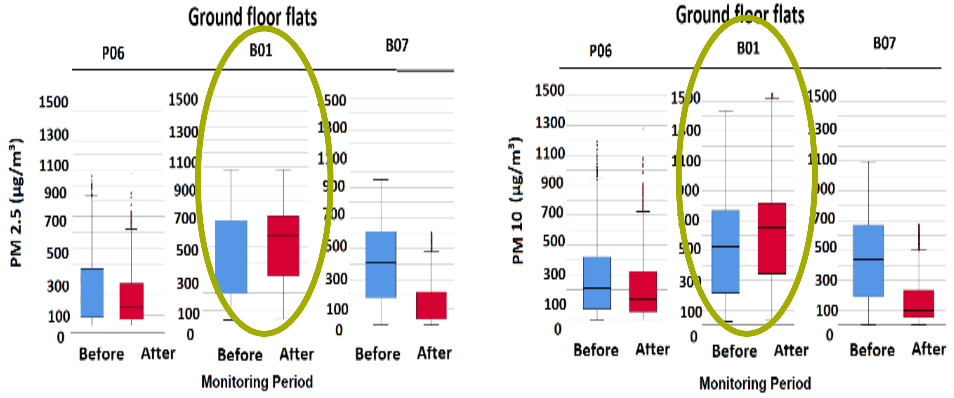




Particulates ($PM_{2.5}$ and PM_{10})

- Strong link was observed between PM levels and personal activities of occupants.
- Levels of PM2.5 and PM10 in flats **P06, B01 and B07** inhabited by smoking residents exceeded recommended limits in both periods (>25 and 50 µg/m³ respectively).
- Daily mean profiles of PMs in P06, B01 and B07 showed that concentrations of PMs followed occupancy - higher during day-times.
- **Flat B01** with limited window opening experienced **highest level of PMs** amongst the three flats due to cigarette smoking and limited window opening.





VOCs and Formaldehyde

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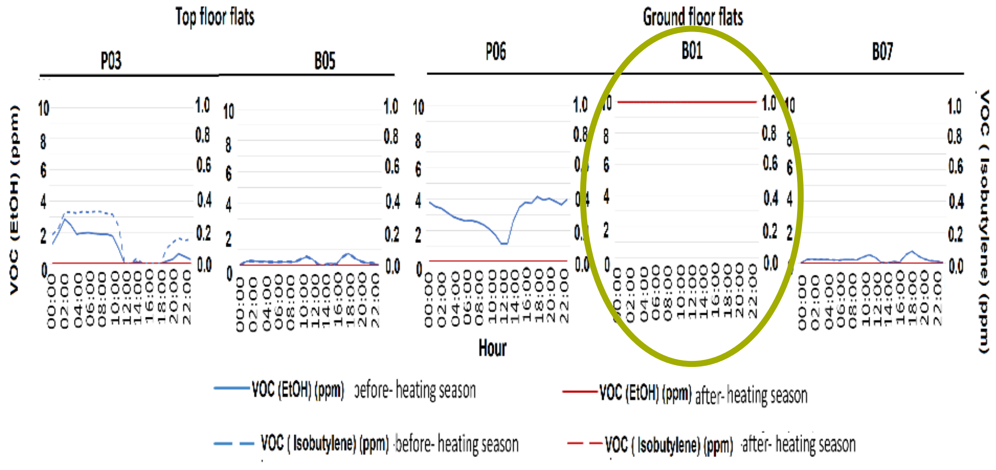
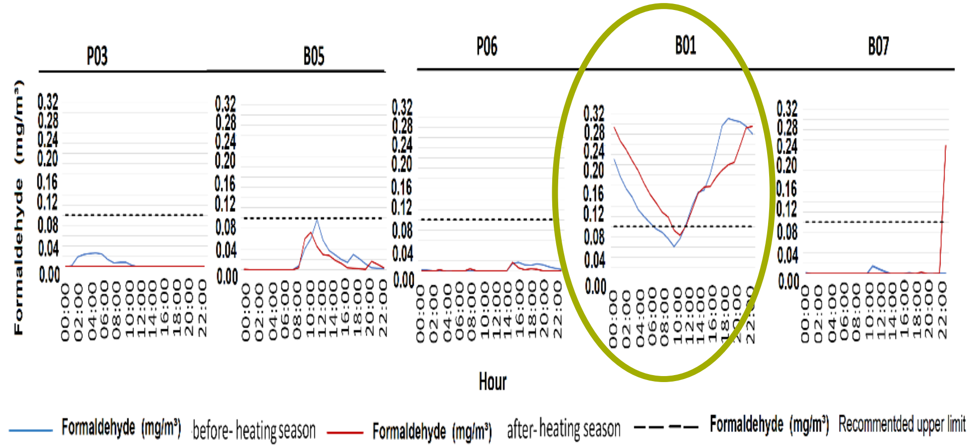
- **Level of VOCs, and formaldehyde were constantly high in flat B01** (> recommended level of 0.1 mg/m^3) due to use of air fresheners to get rid of tobacco smoke and confounded by limited window opening.

- Various spikes in the level of formaldehyde were identified across the flats, due to residents’ use of cleaning products and cosmetics.





Relationship between indoor pollutants

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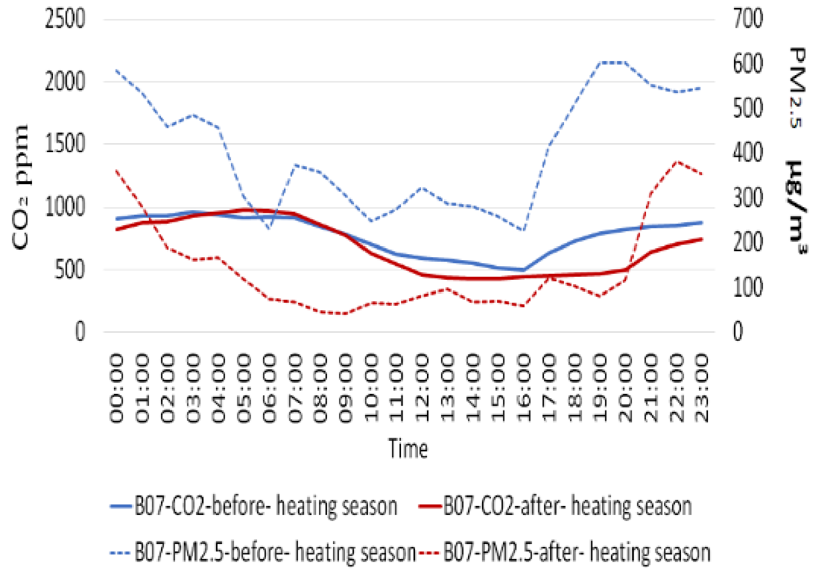
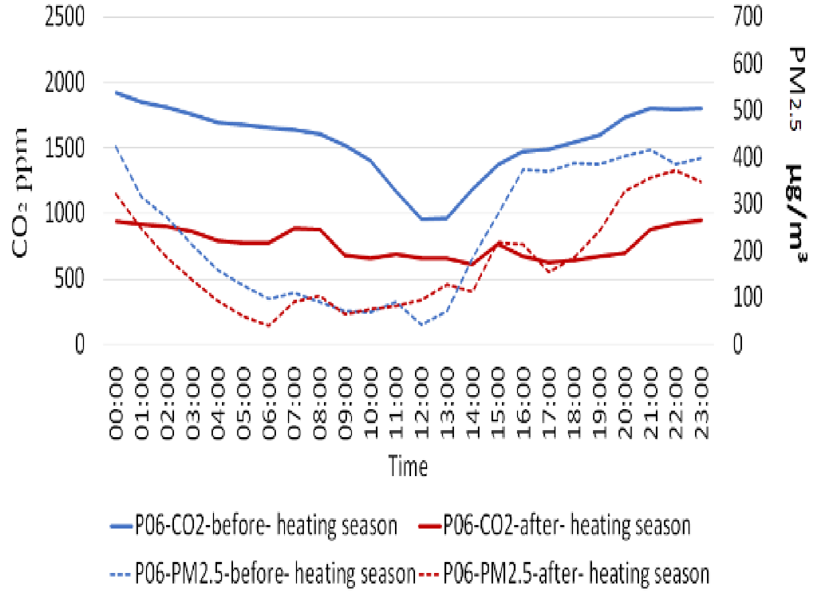
- Despite reductions in levels of CO_2 and PM2.5 levels post-heat pump, the daily profiles followed similar patterns throughout the day.
- CO_2 and PM2.5 levels rose from 12 pm until midnight, and reduced from mid-night until morning when the living rooms were unoccupied, indicating impact of occupant activities.





Summary of findings

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- Despite having similar construction, location and occupancy, study revealed diversity in the magnitude and daily pattern of indoor pollutants in a small sample of social housing flats, indicating the need for large-scale studies.
- Significant difference was found in concentrations of indoor pollutants in flats that opened windows frequently versus those that did not, implying the linkage between ventilation behaviours and IAQ.
- Occupants' personal activities such as smoking and use of air fresheners were found to be closely related to the prevalence of $PM_{2.5}$ and PM_{10}, as well as VOCs ethanol and Isobutylene.
- Since in flat B07, levels of $PM_{2.5}$ and PM_{10} remained above the recommended upper limits despite window opening, this reinforces the need for integrating continuous background ventilation that can be demand controlled, such as trickle vents opening further as the levels of these pollutants rise.
- Vital in homes with low temperature heat pumps that could quickly lose heat with purge ventilation.

Project REFINE:

Pre-retrofit IAQ assessment in houses

Project context

Oxford Brookes University

- Whole house retrofit of 30-40 dwellings (EPC rating of D/E) in Warwickshire.
- Improvements include; external wall insulation, loft insulation, high-performance triple glazed windows, mechanical ventilation with heat recovery and suspended floor insulation.
- Aim is to exceed 50 kWh/m^2 annum where possible with an external insulation system that would allow residents to remain in situ during the retrofit.
- Monitoring of the indoor environment pre- and post retrofit.
- Currently conducing pre-retrofit IAQ monitoring from Feb 2022 to Apr 2022 at 15’ intervals

Indoor temperature: living room and bed rooms

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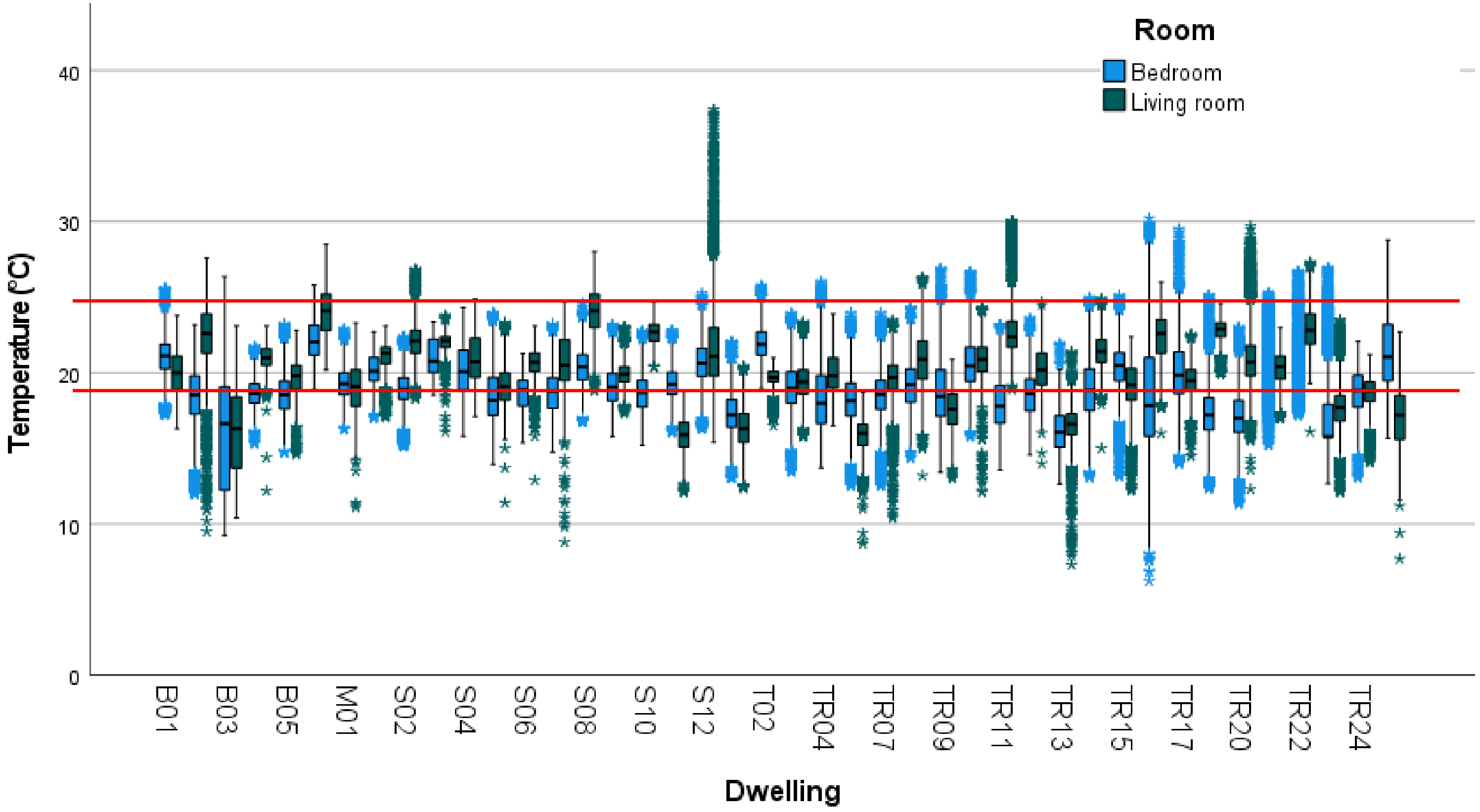
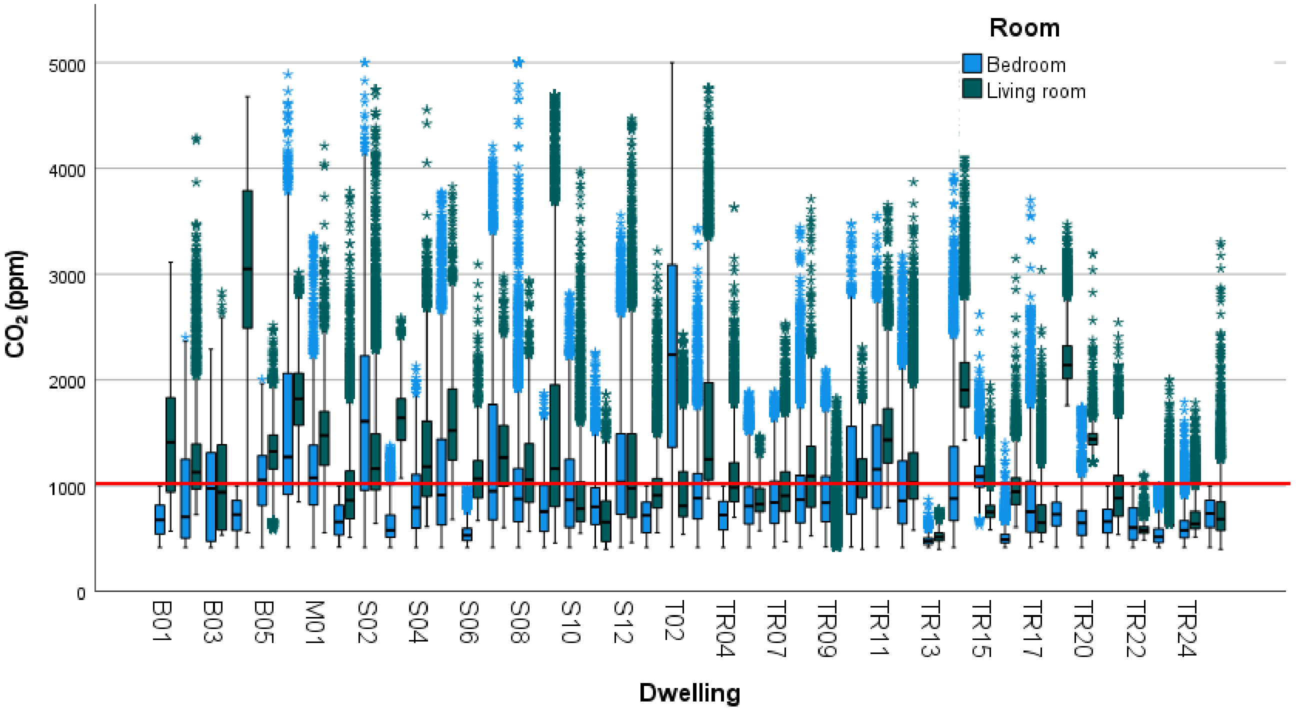
- Mean indoor temperatures were measured to be between 17-20^{o}C in the living rooms and bedrooms.
- Undereating was prevalent with temperatures frequently recorded below 15^{o}C.
- *Triangular semi-detached* properties experienced some of tl lowest temperatures.
- Temperatures were generally higher in the living room with wider interquartile ranges compared to bedrooms.

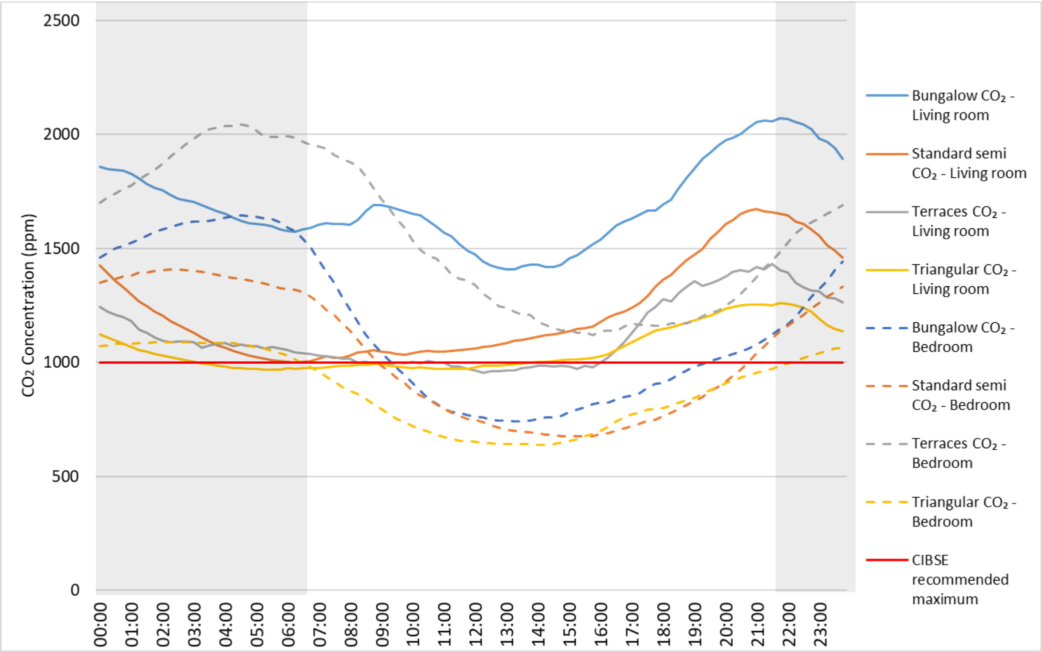


Indoor CO_2 levels

- Almost all bedrooms had high maximum CO_2 level reaching 2000ppm in the terraced properties as compared to 1100ppm in the triangular semi-detached.

- Although living rooms had higher mean CO_2 levels than bedrooms, highest levels were observed during night-time in bedrooms.





Indoor $PM_{2.5}$ levels

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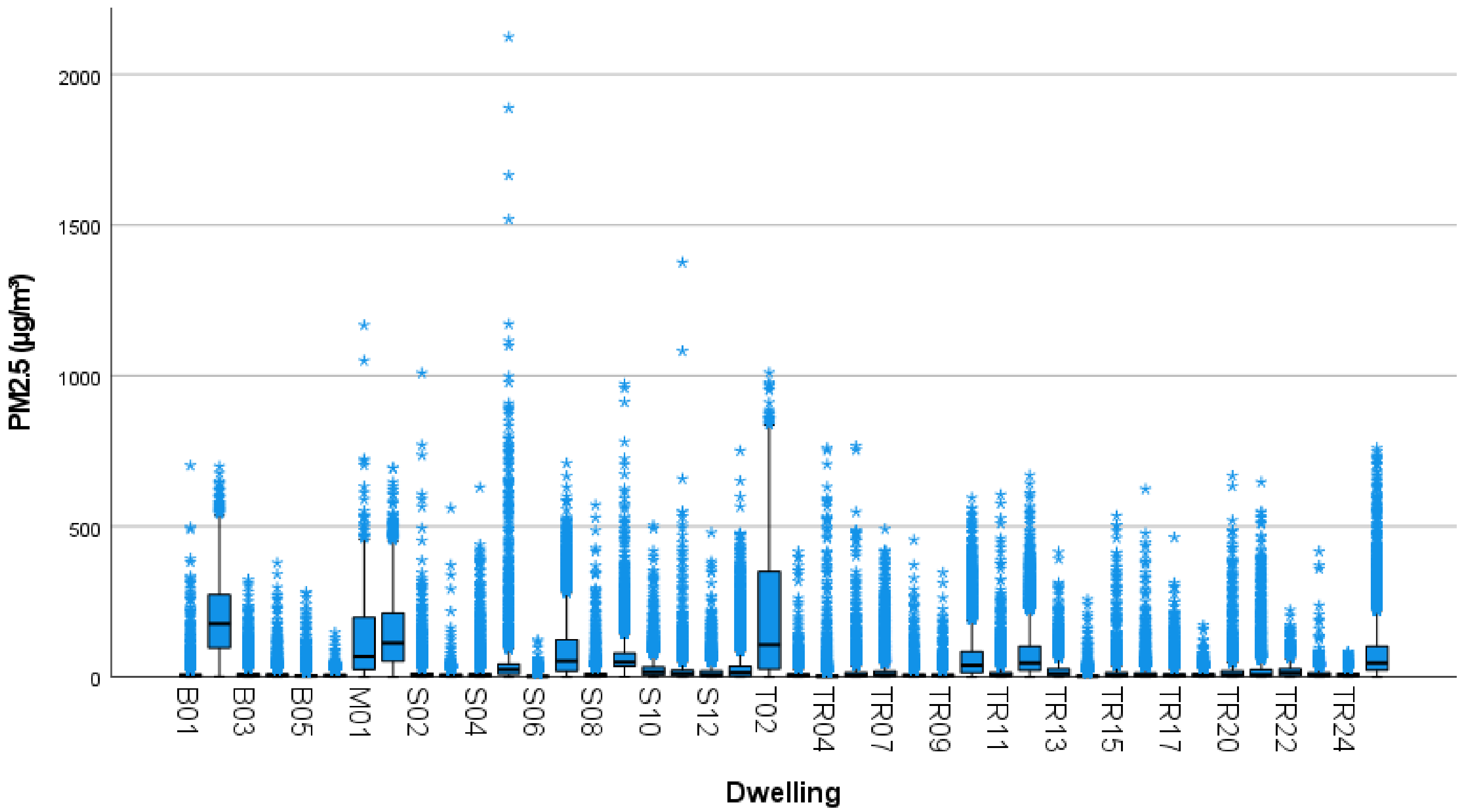
- $PM_{2.5}$ levels varied across the dwellings.
- 10 properties experienced high levels of $PM_{2.5}$ - greater than recommended levels.
- Generally measurements did not exceed 1000ug/m^3, although maximum of 2100ug/m^3 was recorded in some instances.
- *Triangular semi-detached* properties had the lowest overall PM concentrations with the *Terraces* having the highest to reaching 250ug/m^3 and 310ug/m^3



Relationship between CO_2 and $PM_{2.5}$

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- Strong positive correlation found for a Pearson's correlation of 0.92 and a spearman's rank of 0.81.

Pearson's correlation

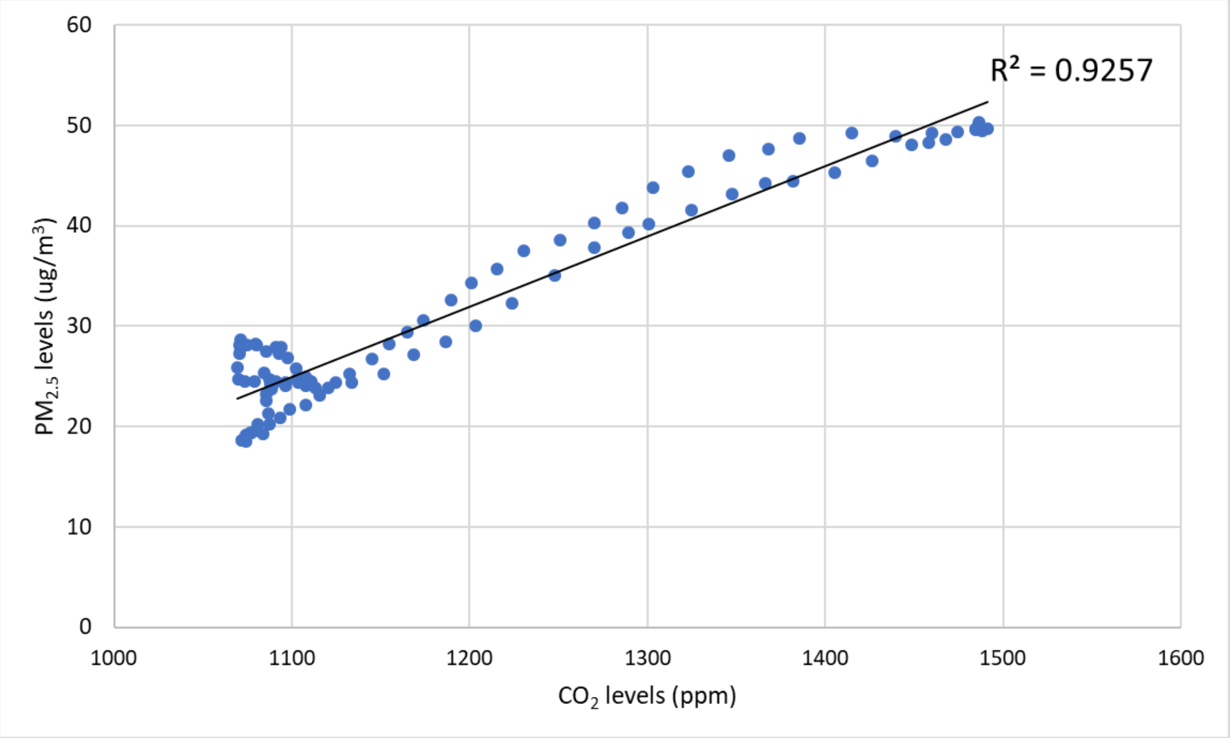
		CO_2 (ppm)	PM2.5 (µg/m³)
CO_2 (ppm)	Pearson Correlation	1	.962**
	Sig. (2-tailed)		.000
	N	96	96
PM2.5 (µg/m³)	Pearson Correlation	.962**	1
	Sig. (2-tailed)	.000	
	N	96	96

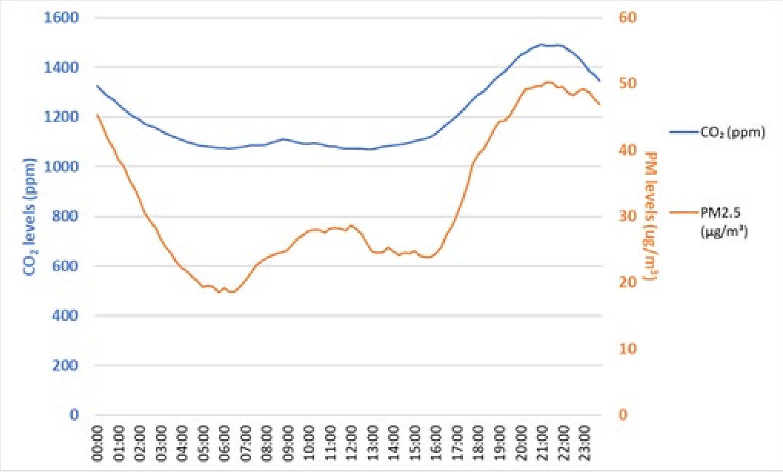
**. Correlation is significant at the 0.01 level (2-tailed).

Spearman's rank correlation

			CO_2 (ppm)	PM2.5 (µg/m³)
Spearman's rho	CO_2 (ppm)	Correlation Coefficient	1.000	.812**
		Sig. (2-tailed)	.	.000
		N	96	96
	PM2.5 (µg/m³)	Correlation Coefficient	.812**	1.000
		Sig. (2-tailed)	.000	.
		N	96	96

**. Correlation is significant at the 0.01 level (2-tailed).

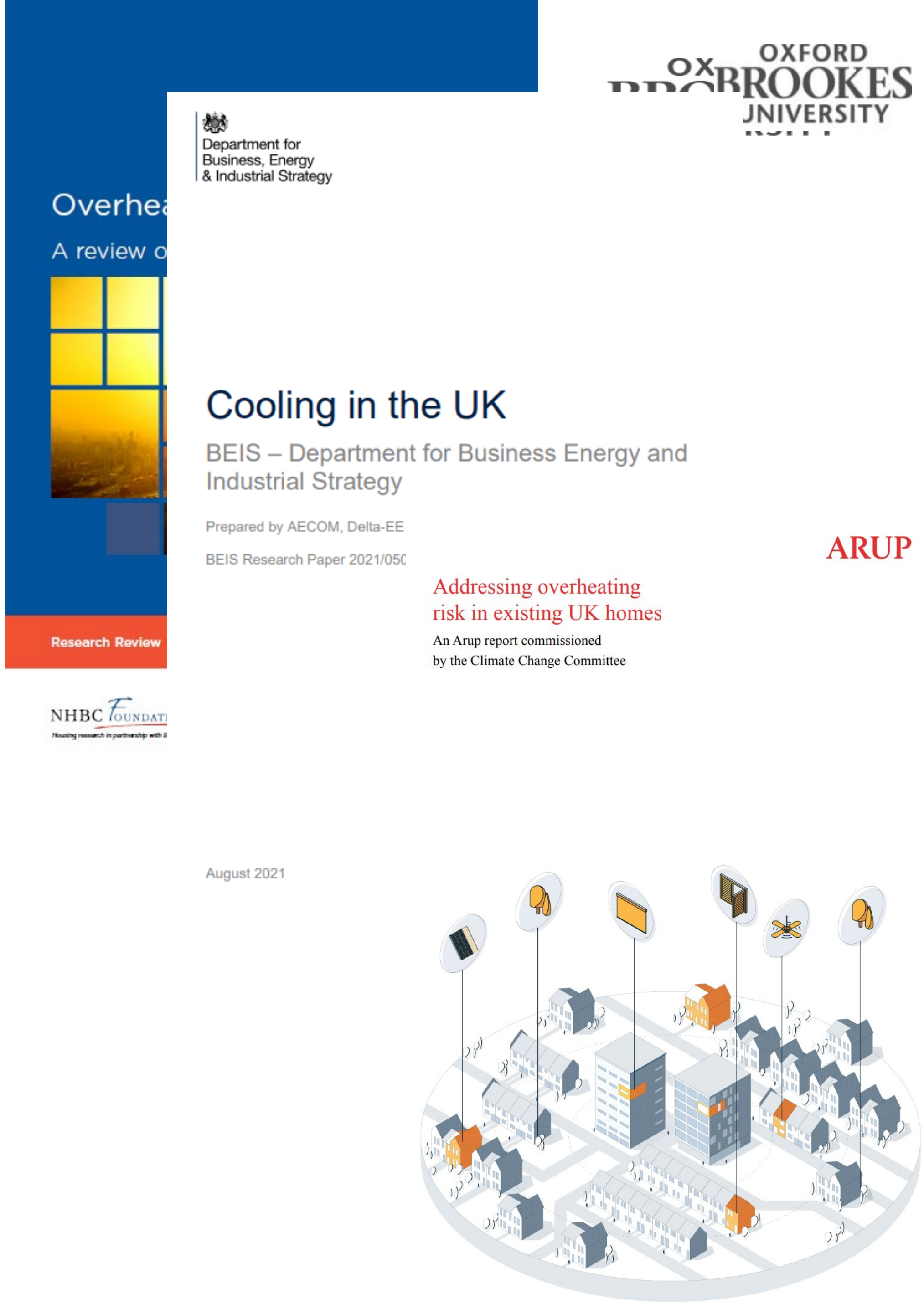




Overheating in homes

Overheating in homes

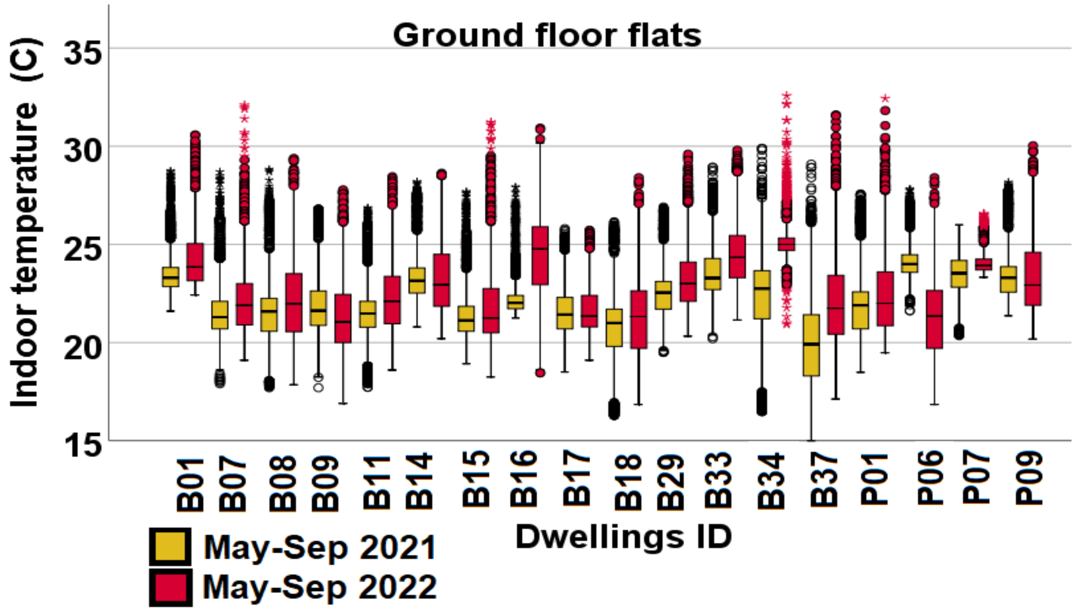
- Summertime overheating in **both new and existing dwellings** is widespread and increasing, even in temperature climates.
- Research has shown the extent, severity and causes of overheating.
- With a warming climate, the prevalence of summertime overheating will get worse.
- According to BEIS report (2021), by the end of the century, it is estimated that the domestic stock will require 75% to 85% of the cooling energy consumption.
- Recent Arup report for Committee on Climate Change confirms that:
  - Nine out of 10 UK homes will overheat at 2° C warming.
  - Smaller houses and flats are at greatest risk.
- Overheating effects mortality and morbitity, with the elderly and vulnerable particularly affected.

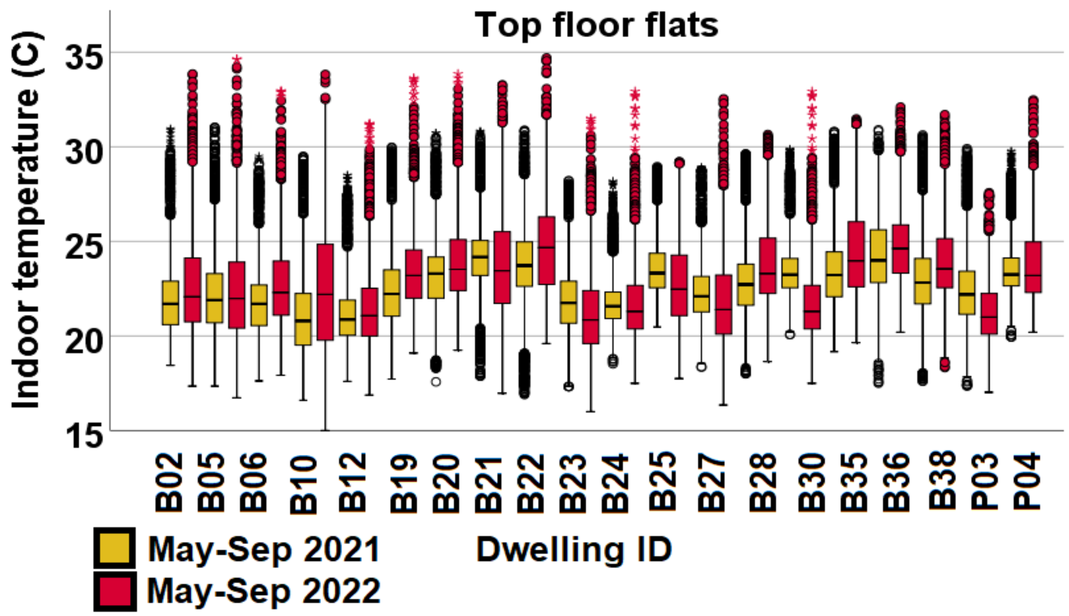


Longitudinal study of summertime overheating in Oxford social housing dwellings (2021 – 2022) – monitoring results

- Top floor flats experienced higher indoor temperature and greater risk of overheating than ground floor flats

- Southwest facing bedroom in flats experienced highest min., mean and max temperatures.





Final thoughts

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- Net zero transition includes decarbonisation of home heating and gas cooking, that would be beneficial for IAQ. However building energy efficiency improvements have potential to reduce ventilation and potentially degrade IAQ if they are not implemented well. There needs to be holistic consideration of energy efficiency and IAQ from the design stage, which is currently lacking.

- Reducing emissions at source may be particularly impactful in energy retrofits with reduced ventilation rates. Changes in indoor pollutant concentrations and consequential health benefits need to be empirically evaluated to strengthen economic case for investment.

- Given the diversity in the concentrations of different indoor pollutants observed across even a small sample of flats and houses, it is clear that indoor environment is highly heterogeneous.

- Vital to measure IAQ parameters in buildings across the UK (large-scale) and over time (longitudinal). Consider representative buildings and those most vulnerable.

- **National Observatory on IAQ in housing** could address these needs and become the ‘Go To’ place for data and evidence for: housing providers, policy-makers and industry.

Thank you for your attention!

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