Quantifying the trade-offs between indoor air quality and energy efficiency in a specialised test facility.

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Abstract

Domestic cooking is a key contributor to poor indoor air quality (IAQ) and one of the most significant indoor sources of particulate matter, including ultrafine particles (UFPs). Since cooking forms an essential part of domestic life, cost-effective active abatement strategies are necessary to improve IAQ. Increasing the ventilation rate by natural or mechanical means will reduce cooking related UFP concentrations but can lead to domestic heat loss: this represents an IAQ and energy efficiency dichotomy. In this study a specialist test facility is used to explore this dichotomy during short-duration cooking activities replicated under different ventilation scenarios, both related to natural and mechanical ventilation in the kitchen, and the relationship between ventilation and airflow around the home more generally. We relate our results to the recently introduced World Health Organization (WHO) good practice statement on UFPs to determine good IAQ. Energy penalties associated with heat loss are calculated to determine which combinations of behavioural and technological interventions can best balance the competing demands of good IAQ and energy efficiency. It was seen that IAQ benefits were achieved at little detriment to energy efficiency. For natural ventilation, behavioural interventions such as opening windows for 20 minutes yielded significant IAQ benefits, reducing UFPs from peak values by 86%. Similarly, 20 minutes of mechanical extract ventilation operation yielded IAQ benefits, reducing UFPs from peak values by 94%. However, in all ventilation scenarios UFPs remained above the WHO good practice high threshold for ~1 hour. All mechanical extract ventilation scenarios resulted in lower energy penalties than for natural ventilation. Our experiments also show that airflow within the house is important to consider when looking at the IAQ and energy efficiency dichotomy. Whilst results are primarily concerned with managing IAQ and energy efficiency under domestic cooking scenarios, there are wider implications for balancing IAQ and energy efficiency, which have increasing importance in light of management of the COVID-19 and energy crises and future policy, such as the Future Homes Standard.

Keywords: indoor air quality, ultrafine particles, cooking, ventilation, heat loss, energy efficiency

1. Introduction

The COVID-19 and global energy crises have thrust the challenges of managing buildings back into the limelight. A principal challenge pertains to promoting buildings that are conducive to occupant health and wellbeing, and that meet environmental targets associated with greenhouse gas emissions and energy efficiency. This tension typically manifests as a dichotomy between managing indoor air quality (IAQ) and energy efficiency: in particular through enacting appropriate ventilation strategies. Through the introduction and circulation of outdoor air to remove or dilute contaminated indoor air, ventilation can promote good IAQ. However, it makes up a sizeable proportion of the energy consumption in buildings through ventilation-related heat loss (Dimitroulopoulou, 2012; Guyot et al., 2018).

Decarbonising the UK building stock is a core part of the UK Government's Net Zero Strategy (HM Government, 2021b). In 2021, domestic environments were responsible for ~16% of greenhouse gas emissions (HM Government, 2023), and a range of different technologies and practices are suggested to achieve Net Zero buildings, including the wider use of insulation to reduce heat loss (HM Government, 2021a). Improved insulation in the UK's building stock will make dwellings more airtight and thus reduce the amount of energy required for heating. However, with improved rates of insulation there is the potential for increased accumulation of indoor generated pollutants (Petrou et al., 2022). Standards for acceptable ventilation rates are included in Part F of the Building Regulations (HM Government, 2010), though these have primarily been designed with a focus on energy efficiency rather than IAQ. During the COVID-19 pandemic the critical role of IAQ in influencing human health was brought to light (Settimo and Avino, 2021), and subsequently there has been a renewed focus on the role of ventilation in reducing exposure to poor IAQ, both for biological agents like SARS-CoV-2, but equally for other indoor air pollutants. Actions to improve IAQ, made necessary by the spread of COVID-19, have led to an increase in manual air changes (opening of windows) in order to dilute pollutant concentrations and reduce indoor exposures (Settimo and Avino, 2021). IAQ should be a priority in the design of buildings (Coggins et al., 2022), and focus is needed to ensure that energy efficiency interventions are administered with IAQ equally in mind (Settimo and Avino, 2021). With more individuals choosing to adopt hybrid or remote working practices, indoor air pollution exposures in the domestic environment will have an even greater impact on health and wellbeing (Coggins et al., 2022). While this paper is focussed on the retrofit and existing building sectors, it is clear that substantial efforts to increase airtightness in new homes in the UK are underway. This is indicated in a recent wide-ranging consultation about the future of new build homes which shall come into force in 2025 (HM Government, 2021c). New building regulations require an air permeability figure of up to 10 ($m^3/m^2.h$ at 50Pa) (HM Government, 2024), but with good practice placing this figure at 5 ($m^3/m^2.h$ at 50Pa). The Future Homes Standard consultation presents two options; one to keep the air permeability at 5 ($m^3/m^2.h$ at 50Pa) with intermittent mechanical extract ventilation, and natural ventilation, the second option is to reduce the air permeability to 4 ($m^3/m^2.h$ at 50Pa) with a continuous mechanical extract system. The latter of these options will have a pronounced effect on possible IAQ through increasing the airtightness.

The effects of poor IAQ on public health are becoming better understood. Globally, illness from poor IAQ results in over five million premature deaths every year, multi-million dollar losses due to reduced employer productivity, and increased health system expenses (González-Martín et al., 2021). While the majority of these premature deaths are occurring in low- and middle-income countries (World Health

Organization, 2014), poor IAQ is still a significant concern in high-income countries. Many unknowns remain, especially in domestic environments. This is in part due to the general lack of IAQ data, and a limited capability to monitor and predict spatial and temporal trends over time (Air Quality Expert Group, 2018): currently, evidence of domestic IAQ largely comes from individual research studies in specific settings, which measure different indoor air pollutants (Air Quality Expert Group, 2022). It follows that standards for acceptable concentrations of indoor air pollutants are less well defined than for outdoors. Regulations and guidelines affecting IAQ come from a wide range of sources which are not as well understood nor effectively implemented (Air Quality Expert Group, 2018). Moreover, advisory health-based guideline values on selected indoor air pollutants issued by the WHO and the United Kingdom Health Security Agency (UKHSA) have no statutory underpinning (Air Quality Expert Group, 2018).

The IAQ and energy efficiency dichotomy is acutely felt in domestic environments. Domestic environments have significant sources of indoor air pollution, including ingress of outdoor air, human activities (such as cooking and cleaning), building construction materials, and furnishings (Bekö et al., 2020). Cooking is conducted on an almost daily basis in most residences (O'Leary et al., 2019a), and is a major source of domestic indoor air pollution (Farmer et al., 2019; Logue and Singer, 2014; Patel et al., 2020), generating significant amounts of particulate matter (PM) and gaseous pollutants (Lai and Ho, 2008; Laverge et al., 2011). Researchers have investigated cooking emissions in real-world environments, where emissions are influenced by many factors (including room arrangement, building materials, outdoor infiltration, other combustion devices, ventilation, and cooking methods), and in controlled chambers, where there are fewer external influences and emissions are largely influenced by the type of fuel and the type of food being cooked (Huboyo et al., 2011). Reported emission rates for the cooking of single ingredients (Afshari et al., 2005; Dennekamp et al., 2001; Isaxon et al., 2015; O'Leary et al., 2019a; Wallace and Ott, 2011) and full meals (He et al., 2005) are highly variable. In the HOMEChem study, cooking activities were the primary source of indoor submicron particles. During cooking events, large enhancements in particle mass occur, with a substantial fraction of these increases due to chemical species related to cooking oils, and by number, these cooking associated particles were predominantly in the ultrafine mode (Farmer et al., 2019; Patel et al., 2020). Similarly, in a study by Shen et al (Shen et al., 2021) the predominant indoor pollutant source was cooking, leading to occasional high $PM_{2.5}$ spikes and differences between rooms dependent upon pathway distances from sources.

Cooking elevates concentrations of ultrafine particles (UFPs), particles which have a diameter ≤100 nm, the measurement of which has been the focus of many studies (Dennekamp et al., 2001; Xiang et al., 2021; Zhang et al., 2010). An approach to focus on monitoring of UFPs is chosen since most particles generated by cooking are within the ultrafine and fine particle size ranges (Abdullahi et al., 2013) and from an epidemiological perspective, these particles may exert higher toxicity (Ohlwein et al., 2019) causing more detrimental health effects. At present there are no air quality standards for UFPs anywhere in the world (Air Quality Expert Group, 2018). However, the WHO have recently introduced a good practice statement to distinguish between high and low ambient UFP concentrations, recognising their significant effects on health (World Health Organization, 2021).

Ventilation is the primary method of reducing cooking-related PM exposure, whether by mechanical extract ventilation, with in-built ventilation and/or fume extraction systems, or natural ventilation through window opening. Mechanical extract ventilation has been seen to have an important role in providing clean air in more energy efficient, airtight, retrofitted buildings (Coggins et al., 2022). Energy demand for ventilation has been quantified through looking at fan operation, and both the heating of supply air and air that infiltrates from the outside (Amanowicz et al., 2023). Ventilation energy challenges faced during the COVID-19 pandemic, a period with a sharp rise in ventilation energy use (Zheng et al., 2021) where energy efficiency became a secondary concern, are discussed in a systematic review (Moghadam et al., 2023).

Managing IAQ and energy efficiency in domestic buildings is critical to both promote health and well-being and meet Net Zero targets. However, a trade-off exists as increasing ventilation to improve IAQ undeniably requires more energy. As one of the dominant sources of poor IAQ in the home, that typically occurs multiple times a day, with the potential for significant exposure to extend beyond the cooking environment, strategies to balance the IAQ-energy efficiency dichotomy during – and following – cooking are especially important. This dichotomy is understudied. Moreover, in a context where buildings are becoming more energy efficient, without careful consideration, there is the potential for IAQ to be exacerbated. This study aims to quantify energy efficiency and IAQ trade-offs through a series of discrete, short-duration cooking events in the kitchen of specialist test facility under different ventilation strategies and using high resolution IAQ monitoring equipment. UFPs are used as a proxy for IAQ, as they are a dominant indoor air pollutant arising from cooking activities, with potential significant health impacts which have been systematically under-reported: indeed, expanding the monitoring of UFPs has recently been recommended by the WHO (World Health Organization, 2021).

2. Materials and Methods

2.1. The Energy House

This study was based at The Energy House at the University of Salford, UK, which is a fully furnished two-bedroom end of terrace house, typical of Salford in 1919 (Ji et al., 2014). Numerous sensors in each room monitor a range of variables (including temperature, air flow velocity, boiler power and, energy usage) using a custom time series program to provide real-time analysis (Ji et al., 2014). The Energy House is located inside a climate-controlled chamber, which can replicate a wide range of weather conditions (Figure 1). In this study the chamber was set to 5.6 °C, typical of wintertime in the UK (Met Office, 2024), when the trade-offs between reducing cooking-related air pollution events and ventilation related heat loss are potentially at their greatest. Thus, the chamber conditions can only be considered representative of those experienced during a calm day during winter. The Energy House and Conditioning Void were maintained at the temperatures used by the UK Government's Standard Assessment Procedure (SAP) methodology for calculating domestic energy use of 21°C in the living room and 18°C in all other zones (BRE, 2021). Internal and external conditions were kept the same for the IAQ and ventilation rate measurements, which were conducted on different dates. In practice, there are of course significant complexities in managing air quality across the indoor-outdoor interface, whereby efforts to remove indoor air pollution through increasing air change with the outdoors inevitably brings in outdoor air, which may also be polluted. However, for the purposes of this study, the use of the Salford Energy Houses' climate-controlled chamber allowed us to focus more specifically on isolating the impacts of cooking sources and ventilation on IAQ, and energy use.

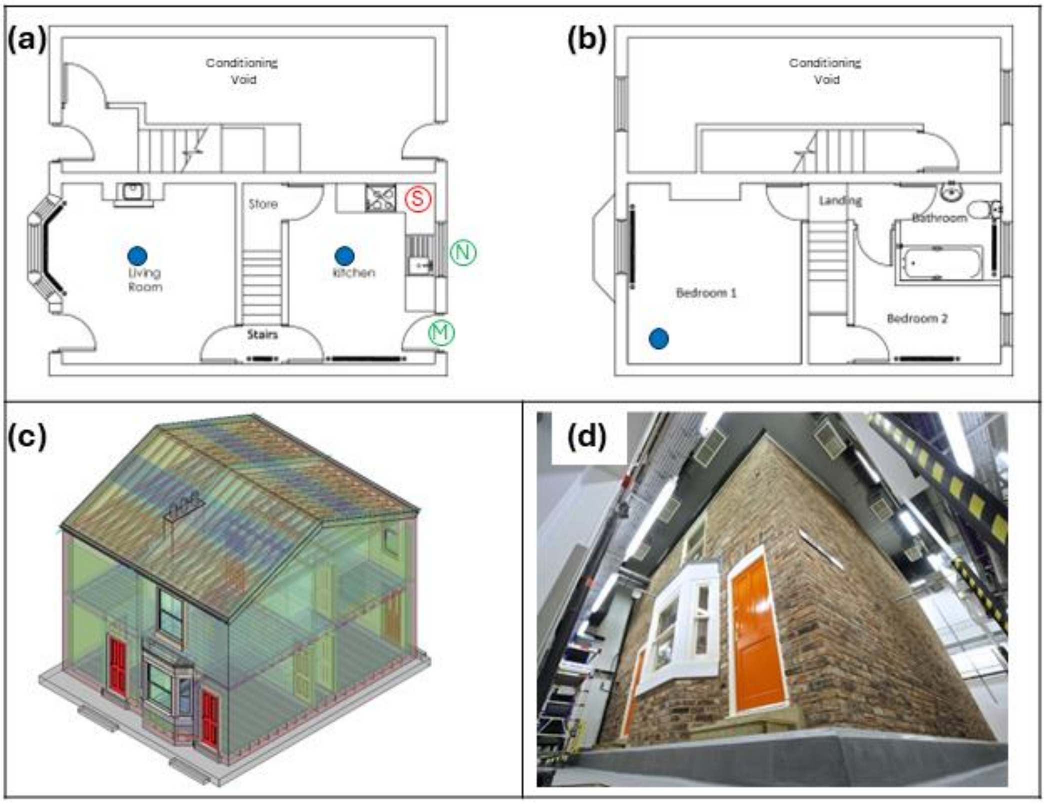

Figure 1: The Energy House floor plans showing (**a**) ground floor showing (S) the location of cooking activities, the location of the kitchen window (N) and (M) the location of the mechanical extract fan (**b**) first floor (**c**) the 3D Energy House model and (**d**) the Energy House in the chamber (Ji et al., 2014). Locations of IAQ monitors are shown with blue circles. The Conditioning Void attached to the house was used to replicate the typical indoor end-terrace environment.

2.2. Air quality measurements and experimental design

Most particles generated from cooking are UFPs (Farmer et al., 2019), which provides justification for their monitoring to determine occupant exposure to cooking-generated particles (Isaxon et al., 2015). Particle number concentration (PNC) – the number of particles in a given volume of air – is commonly used for measuring UFPs as around 90% of the total PNC is in the UFP size range (Morawska et al., 2008). PNC was monitored at 1s intervals using the NAQTS V2000 (V2000), which has an in-built condensation particle counter (CPC) to measure PNC with a lower limit of 15 nm (Gounaris et al., 2024), which is slightly higher than many CPCs which are < 10 nm. The CPC is housed alongside an array of other air quality and environmental sensors (Supplementary Information 1). Prior to deployment the three V2000s were co-located for calibration purposes. One of the V2000s was ISO-27891 calibrated prior to the study and served as a reference unit to normalise the PNC response of the two other V2000s. The V2000s had a correlation coefficient of 0.89-0.90, and a slope between 0.83-0.88 to the reference unit using a 60 second rolling average. They were then situated in different rooms in The Energy House (Figures 1a and 1b). Background PNCs were established and the V2000s were then used to capture PNC for three sets of cooking experiments (Table 1). In this paper measured PNCs are related to the WHO good practice statement on UFPs (World Health Organization, 2021), which designates concentrations greater than 20,000 particles per cm^3 over a 1-hour period as high.[1]

Expt.	**Source**	**IAQ Monitors**	**Ventilation Type**	**Ventilation Period**	**Internal Doors**
1a	Toast	1	None	-	Closed
1b	Toast	1	Natural	From completion of cooking (60 mins)	Closed
1c	Toast	1	Natural	From completion of cooking (20 mins)	Closed
1d	Toast	1	Natural	From completion of cooking (10 mins)	Closed
1e	Toast	1	Natural	From completion of cooking (05 mins)	Closed
2a	Fried Egg	1	None	-	Closed
2b	Fried Egg	1	Natural	From completion of cooking (60 mins)	Closed
2c	Fried Egg	1	Natural	From completion of cooking (20 mins)	Closed
2d	Fried Egg	1	Natural	From completion of cooking (10 mins)	Closed
2e	Fried Egg	1	Natural	From completion of cooking (05 mins)	Closed
2f	Fried Egg	1	Mechanical	From onset of cooking	Closed
3a	Toast	3	None	From completion of cooking (60 mins)	Open
3b	Toast	3	Natural	From completion of cooking (20 mins)	Open
3c	Toast	3	Natural	From completion of cooking (05 mins)	Open

[1] Note that the WHO good practice statement on UFPs suggests that measurements should be made with a lower limit of ≤ 10 nm. However, the V2000 has a lower limit of 15 nm. In practice, this means that we will be slightly under-reporting PNCs.

Table 1. Replicated cooking activities (toasting and frying) over the four consecutive days of monitoring at The Energy House. Further experimental details: number of IAQ monitors, ventilation type and duration, and housing configuration are given.

All cooking was conducted in the kitchen, in most instances with the internal door to the living room closed. Three consecutive sets of experiments were undertaken. In the first set, white bread was toasted for 5 minutes on the highest setting and the kitchen sash window was opened by 250 mm for different periods of time once cooking had ceased (Table 1). In the second set, a single egg was fried over an electric hob and the kitchen was naturally ventilated for the same time periods as described previously, plus for an additional mechanical extract ventilation scenario. Mechanical extract ventilation (using a Simply Silent DX150 intermittent extract fan mounted in the external doorframe) was used from the onset of cooking for 30 minutes. Our ventilation approach was an attempt to mimic real-world practices of using ventilation, including 'shock' natural ventilation to remove indoor generated air pollution once cooking had completed, and mechanical ventilation for certain cooking activities. The third set of experiments replicated toasting activities with internal doors in the Energy House open. This changed airflow throughout the house and subsequently opportunities for dispersion and deposition of UFPs. Before each individual experiment, the pans and cooking utensils were cleaned in warm water and hand dried. At the end of each frying event, the hob was turned off and a lid was placed over the frying pan to prevent continued emissions, using a similar protocol to O'Leary et al. (O'Leary et al., 2019a).

2.3. Ventilation rate measurements

The ventilation rate of the kitchen in air changes per hour (AC/H) was measured using the tracer gas decay method outlined in ASTM E741-11 (2017). CO_2 was released into the kitchen with the window in the closed and open positions and all internal doors closed. CO_2 concentration measurements were taken at the centre of the kitchen at 30s intervals using a Sauermann Si-AQ Expert IAQ monitor (Si-AQ) (uncertainty ± 2% reading or ± 10 ppm), for each natural ventilation scenario (Supplementary Information 2). These measurements were conducted independent of the cooking experiments as the ventilation periods associated with these experiments were deemed too short to obtain robust measurements of AC/H. A ventilation period of one hour in duration was used to undertake the CO_2

decay measurements. A TSI / Airflow PH731 electronic balometer (± 3% reading and ± 4 l/s) was used to measure the extract rate of the mechanical ventilation system.

2.4. Kitchen heat load measurements

The steady state space heating requirement of the kitchen in Watts (W) at 5.6 °C external temperature was measured prior to the ventilation rate measurements. Electric resistance heaters with thermostatic controllers maintained SAP internal temperatures in each zone of the Energy House and Conditioning Void. Conditioning of the internal and external environments commenced 48 hours prior to the measurements so that heat transfer between the internal environment of the Energy House and the chamber was considered akin to steady state (Farmer et al., 2017). Fibaro smart wall plugs (uncertainty ± 1%) were used to measure the space heating power input for each zone. Time constraints meant that it was only possible to accurately measure space heating power requirements without additional ventilation provision.

2.5. Calculating energy penalties

This study considers increases in energy consumption attributable to space heating demand and the operation of natural and mechanical extract ventilation systems. Energy penalties are defined as the additional energy consumption required to maintain the internal setpoint temperature during periods of increased ventilation to improve the IAQ. These energy penalties were calculated using the energy required to heat additional air change with the external environment based on the ventilation rate measurements.

2.5.1. Natural Ventilation

The energy penalty for a window opening ventilation period was obtained using the following equation.

$$E_p = (E_h - E_c) + E_v$$

Where:

E_p= Energy penalty that includes additional heat input from cooking appliance

E_h = Energy required to maintain kitchen air temperature with window closed (obtained from energy measurements with the Energy House at steady state (Section 2.4))

E_c = Heating energy input from cooking device during cooking period

E_v = Energy required to heat additional air infiltration required for cooking ventilation (obtained from ventilation rate measurements)

E_v is calculated as;

$$E_v = \frac{\Delta n \; c_p \; \rho \; V \; \Delta T \; t_v}{3600 * 1000}$$

Where:

Δn is the measured increase in the air change rate within the ventilated space[2] (ACH)

c_p is the specific heat of air[3] (J/kg K)

ρ is the density of air[4] (kg/m^3)

V is the volume of the ventilated space[5] (m^3)

ΔT is the temperature difference between the set-point temperature and external environment (K)

t_v is the ventilation period (hours)

2.5.2. Mechanical Extract Ventilation

The energy penalty for a mechanical extract ventilation period was obtained using the following equation.

$$E_p = (E_h - E_c) + E_v + E_f$$

[2] The 3600 value in the denominator accounts for the conversion of ACH to ACS and the 1000 value converts Wh to kWh.

[3] Specific heat of air at 5°C is 1002 J/kg K (Engineering Toolbox, 2020)

[4] Density of air at 5°C is 1.268 kg/m^3 (Engineering Toolbox, 2020)

[5] Volume of kitchen is 26.92 m^3

Where:

E_v = Energy required to heat additional air infiltration required for cooking ventilation (obtained grille flow measurement of extractor fan)

E_f = Energy required for mechanical ventilation over operational period (based on manufacturers literature value of 22.6 W)

3. Results

In this section we first present the PNC results under the different ventilation scenarios (none, natural and mechanical) before presenting energy penalty calculations. The IAQ and energy efficiency dichotomy is explored in the discussion section that follows.

3.1. Indoor Air Quality

3.1.1. Kitchen only (Experiments 1 & 2)

PNC profiles generated by the discrete cooking episodes exhibit similar trends (Figure 2a, 2b). PNC are initially low then increase rapidly over time as cooking progresses, indicating ongoing emissions of UFPs until a peak concentration is reached. Once cooking has stopped, the PNC decays exponentially towards background concentrations with the rate largely governed by the AC/H.

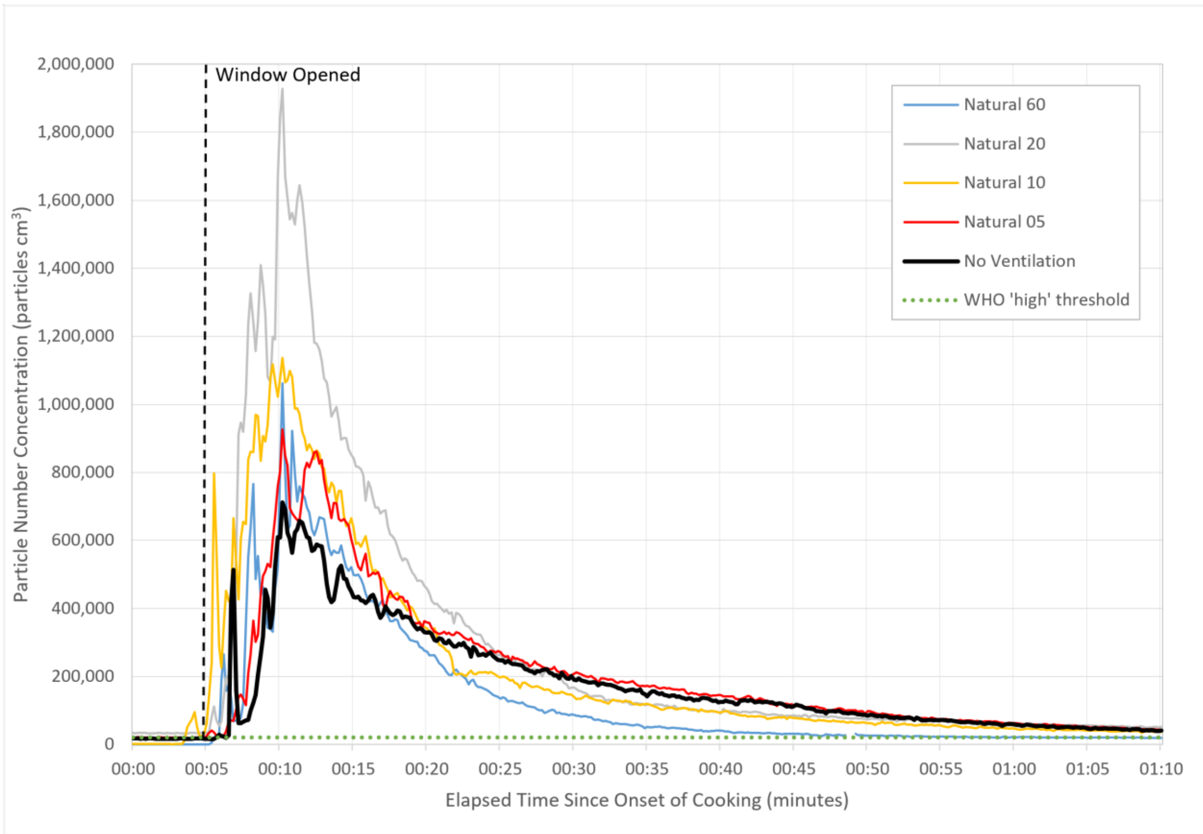

Figure 2a: PNC resulting from cooking toast under different ventilation scenarios. See Table 1 for details of individual experiments and ventilation scenarios corresponding to each scenario.

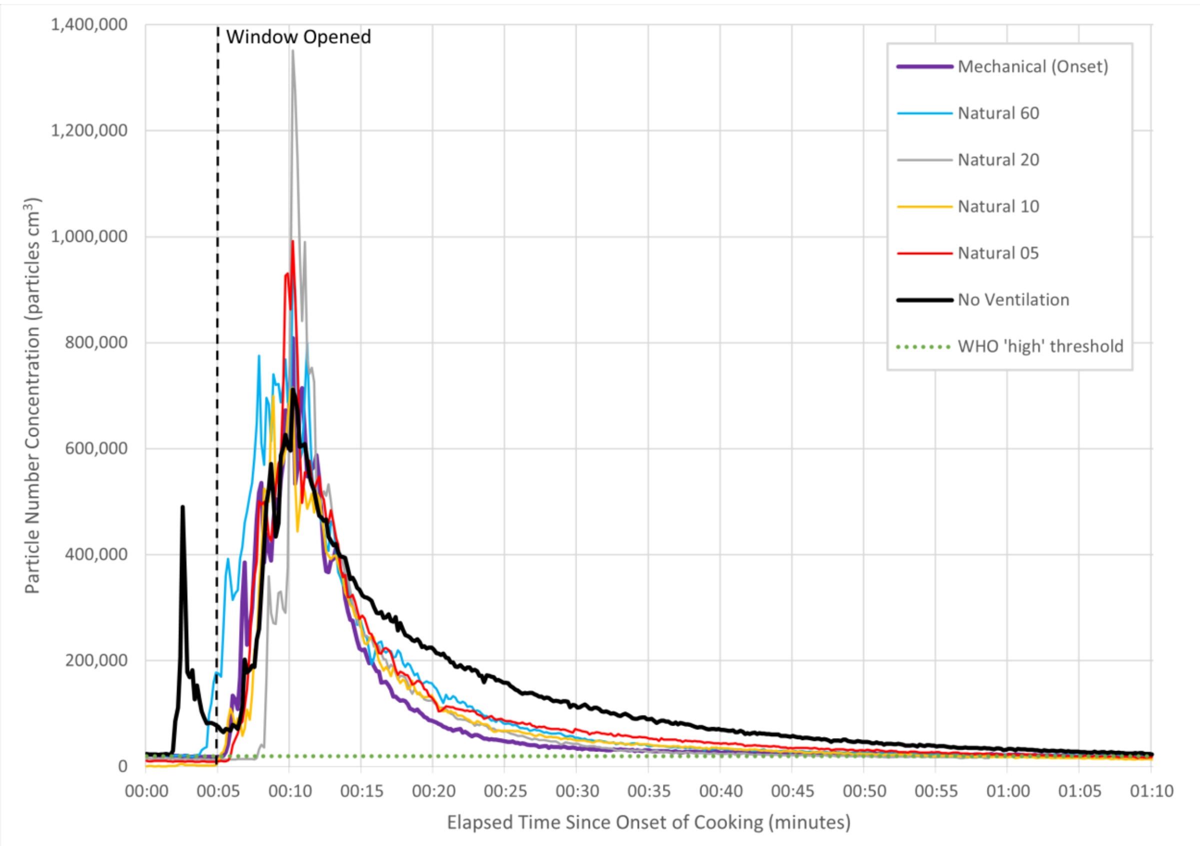

Figure 2b: PNC resulting from frying eggs under different ventilation scenarios. See Table 1 for details of individual experiments and ventilation scenarios corresponding to each scenario.

The PNC profiles highlight significant differences between ventilation scenarios. Peak PNC differed between experiments, reflecting variations in source strength, which had a consequential effect on the time to reduce PNC below the 'high' threshold designated in the WHO good practice statement on UFPs. Ventilation rate is perceived as the dominant force controlling PNC decay.

The rate of decay from peak to background PNC is similar in most scenarios, with the non-ventilated scenarios (Table 1: 1a, 2a) exhibiting slower rates of decay due to reduced AC/H. In ~~some of~~ the ventilated scenarios a higher initial decay rate (first 20 minutes) relative to the subsequent and overall average decay period is observed. The initial decay rate is likely to be dominated by dispersion (promoted by ventilation), whilst other processes, such as deposition are more likely to explain the subsequent slower decline to background levels. It was hypothesised that opening the window for the longest period would elicit the fastest decay rate due to greater AC/H between the kitchen and the chamber. This statement holds true for toasting, and most frying cases. Results for frying based on assessment of decay rates and PNC profiles (Figure 1, Figure 2) suggest mechanical extract ventilation is the most effective mitigation strategy to improve IAQ. This is particularly evident during the higher initial decay rates (first 20 minutes). Based on decay rates, Scenarios 1b (natural ventilation, 60 minutes) and 2f (mechanical extract ventilation) (Table 1) are most effective after toasting and during frying, respectively, reducing PNC from peak values by 86% and 94% respectively after 20 minutes of ventilation.

3.1.2. Whole house (Experiment 3)

PNC data from one near-field (kitchen) V2000 monitor and two far-field (living room and upstairs) V2000 monitors reveal further information about the relationship between ventilation and airflow around the Energy House (Figure 3). Though much lower than in the kitchen, high PNC in other regions of the house, especially the living room, suggest internal transfer of UFPs despite the kitchen window being open and the internal doors being closed. When the kitchen window is open and the internal doors are open, PNC are much lower in the kitchen where the source is located, but much higher in the adjacent living room and upstairs bedroom (Figure 1), with PNC remaining above background levels for longer periods of time. This suggests that to understand indoor exposure to UFPs it is equally as important to consider air changes between rooms as it is between the kitchen and external chamber.

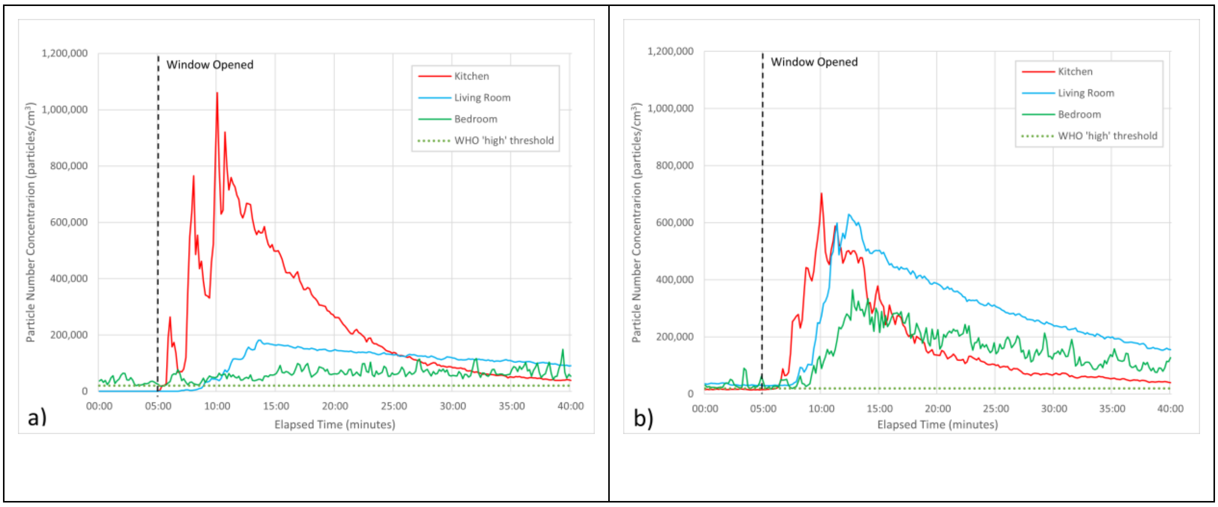

Figure 3: Times-series of PNC recorded in both near-field (kitchen) and far-field (living room and bedroom) locations as a resulting of toasting under naturally ventilated conditions with internal doors (a) closed and (b) open.

3.2. Energy Penalties

As stated previously, an energy penalty is defined as additional energy consumption resulting from actions undertaken to improve IAQ by reducing the concentration of cooking generated UFPs. Measured AC/H were used to estimate additional ventilation heat loss and energy required to heat incoming air for periods of ventilation at 5.6 °C external temperature. Following this, the heat gains associated with the cooking process and its influence on space heating demand were considered.

3.2.1. Ventilation heat loss

Ventilation rate measurements and the energy required to heat the incoming air for different periods of ventilation, without considering additional heat inputs from cooking is shown in Table 2. The electrical power demand of the mechanical extract ventilation system (23 W) is included within the values for heating incoming air in this scenario.

Ventilation	n (ACH)	Ventilation heat loss (W)	Energy required to heat exchanged air (kWh)				
			60 mins	30 mins	20 mins	10 mins	5 mins
Background	2.3	293	0.293	0.146	0.097	0.050	0.023
Window open	7.5	962	0.962	0.481	0.317	0.164	0.077
Extract on	7.0	888	0.911	0.455	0.301	0.155	0.073
Δwindow	5.2	669	0.669	0.335	0.221	0.114	0.054
Δextract	4.7	596	0.618	0.309	0.204	0.105	0.049

Table 2: Air change rates, ventilation heat loss rates, and energy required to heat air exchanged during each ventilation period for the cooking scenarios.

The measured ventilation rate with the kitchen window closed was 2.3 AC/H. This implies that the house is hard-to-treat in terms of energy efficiency and may incur higher rates of infiltration than newer housing stock (Ji et al., 2014). The high AC/H can be attributed to the high air permeability value of 15.7 $m^3.h^{-1}.m^{-2}$ @ 50 Pa when the Energy House is fitted with single glazed timber sash windows: this value is 37% greater than the UK average air permeability value of 11.5 $m^3.h^{-1}.m^{-2}$ @ 50 Pa for homes constructed before 1998 (Stephen, 1998). The ventilation rate increased by 3.3 times and 3.0 times for window opening and extract ventilation, respectively. This suggests that both measures provide similar levels of additional ventilation. However, it must be noted that the sheltered conditions in the Energy House chamber mean that measurements for window opening may only be experienced on calm days in the real-world. The increase in ventilation rate achieved by mechanical extract will be less influenced by external environmental conditions.

The increase in energy associated with ventilation was 3.3 times greater with the window open and 3.1 times greater with mechanical extract ventilation than background ventilation. The mismatch between increases in ventilation rate and energy requirement for mechanical extract ventilation is due the energy consumption of the fan, which accounted for four percent of the increased energy requirement.

3.2.2. Energy Penalty including cooking gains.

The increase in ventilation *heat loss* should be considered alongside the *heat gain* associated with each cooking activity. The energy penalty (E_p) considers heat generated by the cooking processes. In this case the power outputs of the toaster and hob were 1200 W and 1700 W respectively. The power input from each cooking appliance far exceeds the measured steady state rate of heat loss from the kitchen with no additional ventilation of 635 W (this includes fabric and ventilation heat losses). Additional heat input from appliance use will result in a rise in kitchen temperature (under certain circumstances) and could result in overheating, necessitating the requirement for additional ventilation to maintain thermal comfort as well as good IAQ. The calculations assume the toaster is operational for three minutes and the hob for eight minutes (comprises three minutes to heat hob and pan and five minutes cooking time).

When considering the additional heat input from the cooking processes, lower energy penalties are observed likely attributed to lower ventilation heat losses (Table 3). It is observed that more heat can be generated from frying than is lost by additional ventilation heat loss for a 5- or 10- minute period, so an energy surplus is observed (shown as negative numbers in Table 3). In all instances of toasting, an energy penalty is observed, since less energy is generated, but this is negligible for 5- and 10- minute periods of window opening which are insufficient to reduce PNC to below the high threshold designated in the WHO good practice statement on UFPs. For extended periods of natural ventilation, more heat is lost through ventilation than gained through the cooking processes hence the generation of higher energy penalties. When periods of natural ventilation extend beyond 20-minutes, larger energy penalties occur, even when considering the energy generated by cooking activities, due to prolonged periods of air change with the cooler air of the chamber.

Cooking Activity	Ventilation	Energy penalty for ventilation period (kWh)					
		60 mins	30 mins	20 mins	10 mins	5 mins	No Ventilation
Toasting	Window	0.641	0.306	0.193	0.089	0.025	-0.028
Frying	Window	0.531	0.196	0.082	-0.025	-0.085	-0.138
Frying	Mechanical	0.618	0.309	0.204	0.105	0.049	-0.138

Table 3: Energy Penalty (E_p) based on differing ventilation periods for toasting and frying under test conditions.

Energy penalties required to meet the WHO good practice statement on UFPs high threshold (hourly average of less than 20,000 particles per cm^3) will vary across the year. Given the short period of time for cooking scenarios and PNC decays, PNC values often did not drop below the high threshold in our experiments. Therefore, AC/H were calculated using PNC decay curves to allow us to extrapolate decay data to characterise the length of time required to go below the high threshold. For example, on a typical winter day at the Energy House, achieving an hourly average of less than 20,000 particles per cm^3 following the frying of an egg would require a 0.49 h period of window opening, resulting in an increase in ventilation heat loss of 0.328 kWh (excluding cooking gains) and energy penalty of 0.189 kWh. It is important to note that energy penalties will vary depending upon external conditions (Figure 4). For example, the energy penalty at the Energy House for an average December day would be 12 times greater than that in May.

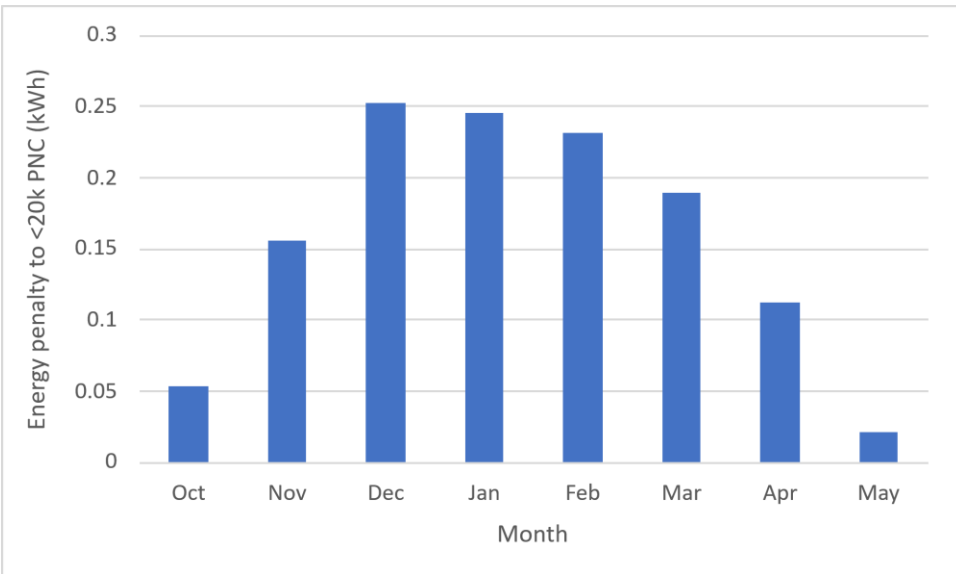

Figure 4: Energy penalty per frying event at the Energy House during each month of the SAP heating season.

4. Discussion

In this study domestic cooking, which is conducted daily in most homes, generated significant UFP concentrations (which we measured as PNC). Since eliminating this source of poor IAQ is neither possible nor desirable, effective mitigation through ventilation is essential to ensure good IAQ and protect the health and well-being of occupants (Singer et al., 2012). Whilst infiltration alone is typically not sufficient to dilute PNC (O'Leary et al., 2018), the higher AC/H (2.3) of the "leaky" Energy House can reduce PNC to some degree, albeit not as effectively as purpose-provided ventilation, in either natural or mechanical extract form. When windows are opened, the AC/H increases from 2.3 to 7.5, and a more rapid and significant reduction in UFP concentrations is observed. Window opening has a more significant effect of reducing the PNC for the first 20 minutes, observed through higher initial decay rates.

Whilst energy penalties are not associated with non-ventilated scenarios, the IAQ penalty is considerable. In the hour during and following cooking experiments the PNC is 5-10 times greater than the UFP concentrations that the WHO regards as high. This IAQ penalty persists for over an hour before UFP concentrations return to background, below the WHO good practice statement on UFPs high threshold of 20,000 per cm^3 over a 1-hour period. Some ventilation is clearly better than no ventilation to increase the rate of removal of internally generated UFPs, however, there are clear energy penalties associated with ventilation. If we *exclude* the energy inputs associated with cooking, the energy penalties are modest and increase over time with extended periods of natural ventilation. If we *include* the heat generated through cooking, the energy penalties associated with natural ventilation are negligible, particularly in the case of frying activities, due to the greater heat input associated with this activity. In this specific study we identified an initial 20-minute window during which IAQ improvements can be achieved with no energy penalties. However, these IAQ improvements do not result in UFP concentrations below the WHO 'high' UFPs threshold. Achieving this threshold requires longer periods of ventilation and subsequent energy penalties.

Mechanical extract ventilation can reduce PNC more rapidly than natural ventilation (Figure 2), despite having a slightly lower AC/H. The rate of ventilation is also more consistent when mechanically driven. The first 20 minutes appear to be the most significant for reducing UFPs and only modest energy penalties were incurred during this period. This leads us to conclude that this initial 20-minute period of mechanical extract ventilation after cooking represents the ideal time to balance the dual objectives of good IAQ and energy efficiency. Energy penalties will increase for longer periods of ventilation, whether natural or mechanical.

Our findings are consistent to those reported in Dobbin et al. (Dobbin et al., 2018) and O'Leary et al. (O'Leary et al., 2019b) where exposure to UFPs and $PM_{2.5}$ was reduced by continuing to ventilate for 10–15 minutes after cooking. These papers acknowledge the trade-offs in long-term mechanical extract ventilation, including the noise generated and energy used, and the impracticalities for use for long periods after cooking (O'Leary et al., 2019b). Therefore, these represent timings where mechanical extract ventilation incurs only a small cost (e.g., heat loss) while the IAQ benefits are considerable. O'Leary et al. (O'Leary et al., 2019b) similarly showed $PM_{2.5}$ concentrations reduce by 58% for 10 minutes of extra ventilation after cooking ends when compared to ventilation during cooking alone. However, increasing the ventilation period to 15 minutes only reduces concentrations by a further 8% demonstrating a diminishing return on IAQ improvement through ventilation. This is akin to our previous finding about ventilating for over 20 minutes with window opening.

4.1. Future work

In this study energy efficiency and IAQ trade-offs were quantified through a series of short-duration cooking experiments in The Salford Energy House. There are clear opportunities to expand upon our findings.

A clear methodology that can be augmented to investigate the IAQ-energy efficiency dichotomy during cooking is outlined in this paper which can be applied to a range of different structural, behavioural, and environmental situations. Whilst the energy penalties observed are low on the order of a single short-duration experiment, they increase significantly when scaled up over a full heating season. Alongside this, further work could more comprehensively examine the effect of seasonality on energy penalties to exposure mitigation (Figure 4). It is anticipated that increased AC/H in the cooling season due to frequent window opening to moderate internal temperatures would promote faster rates of UFP removal. Likewise, higher outside temperatures would also result in lower energy penalties with less need for any temperature recovery in the indoor environment.

It is also important to note that our scaling is based on a single, short-lived cooking event per day, whereas in the 'real-world', cooking is often done sequentially (Farmer et al., 2019; Patel et al., 2020), and is shaped by a range of different cultural, and social factors, including different cuisines and cooking styles. Therefore, we would expect a more complex and varied set of relationships between IAQ and energy efficiency due to more complicated cooking and ventilation regimes. This complexity is of particular importance when characterising exposure to UFPs, as in our set of discrete experiments we were able to let concentrations return to near-background concentrations. However, in a real-world setting, with more frequent use of sources of UFPs, this would be more difficult. The implications of this are that occupants are likely to be exposed to high concentrations of UFPs (as designated by the WHO) for longer periods of time.

Likewise, future research could follow a similar methodology to examine trade-offs between IAQ and energy efficiency in either test or real-world environments across different segments of housing stock, with differing atmospheric conditions that influence natural ventilation, outdoor air quality, and with different mechanical extract ventilation systems. Importantly, future work needs to reflect ongoing increases to the airtightness of the UK housing stock, which will likely change how the IAQ-energy efficiency dichotomy manifests. This work will be developed using two newly created test homes that have recently been built in the Energy House 2.0 test facility at the University of Salford. These homes closely resemble fabric and service provisions as suggested in the current Future Homes Standard (Fitton, 2024a, b). Moreover, future research could evaluate the efficacy of supplementary air cleaning technologies in managing the IAQ-energy efficiency dichotomy (Lowther et al., 2023). These devices can help to provide ‘equivalent’ air change rates in settings where ventilation is more difficult, as evidenced during COVID-19 (Morawska et al., 2024). There is a long history demonstrating the efficacy of HEPA filters in reducing indoor PM by ~30-80% (Kelly and Fussell, 2019). For example, Batterman et al. (Batterman et al., 2012) demonstrated an ~50% reduction in PM in low-income homes with asthmatic children. Likewise, Batterman et al. (Batterman et al., 2005) demonstrated 30-70% reductions in PM in homes with smokers. Moreover, the efficacy of using multiple HEPA filters around the home has been evaluated, with similar reductions in PM (Lowther et al., 2023). Alongside HEPA filters, there are a range of other emerging air cleaning technologies, such as UV irradiators and adsorption systems. However, the evidence on their reduction in PM is less clear than for HEPA (Booker et al., 2025).

This study also illustrated that activities in one indoor location (e.g. cooking in the kitchen) had significant impacts on IAQ across the house. This characterisation is important to develop models of personal exposure in indoor environments. For example, occupants are not just exposed to cooking related UFPs in the kitchen but can also be exposed to concentrations greater than the WHO high threshold in bedrooms overnight. This outlines both that pollutants migrate around the domestic environment, but also that additional ventilation in other rooms may be essential to reduce exposure. Moreover, to balance the conflicting objectives of minimising energy consumption and maximising IAQ, ventilation systems must be modernised, shifting from space-based designs to occupant-based designs in domestic environments (Amanowicz et al., 2023; Moghadam et al., 2023), which can better adjust to occupant needs. Guyot et al. (Guyot et al., 2018) have shown that significant energy savings of up to 60% can be obtained without compromising IAQ with demand-controlled ventilation due to a lower demand for ventilation airflow and thus a lower amount of energy to drive fans.

5. Conclusion

This study investigated the trade-offs between the dual objectives of good IAQ and energy efficiency. Through conducting a series of short-duration discrete cooking activities in a specialised test facility, energy penalties associated with reducing UFPs were characterised under different ventilation scenarios.

This study in the Energy House has shown that improvements in IAQ can be made with no energy penalties for short periods of time up to 20 minutes. Both natural and mechanical extract forms of ventilation can lead to substantial reductions in UFP concentrations during this window, with mechanical extract ventilation being particularly effective. However, ventilation needs to extend beyond 20 minutes for UFP concentrations to drop below the WHO high threshold for UFPs, and energy penalties are incurred as a consequence. Therefore, a clear balancing of the dichotomy can be achieved over shorter periods of time, but it remains problematic over a longer period of time. Nonetheless, ventilation for up to 20 minutes after a cooking event may be a reasonable suggestion and potentially memorable making it appropriate to encourage behaviour change.

Over the past few decades building management and research has been largely focused on promoting energy efficiency resulting in the unintended consequence of an IAQ and energy efficiency dichotomy. The emergence of COVID-19 has interrupted this balance by encouraging substantially increased ventilation rates to improve IAQ at the expense of energy efficiency. However, ventilation practices to manage COVID-19 are now being balanced against other contemporary issues including the ongoing energy crisis and plans to meet UK Net Zero targets. These competing factors highlight the continued importance of managing tensions between IAQ and energy efficiency.

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Quantifying the trade-offs between indoor air quality and energy efficiency in a specialised test facility.

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Abstract

Domestic cooking is a key contributor to poor indoor air quality (IAQ) and one of the most significant indoor sources of particulate matter, including ultrafine particles (UFPs). Since cooking forms an essential part of domestic life, cost-effective active abatement strategies are necessary to improve IAQ. Increasing the ventilation rate by natural or mechanical means will reduce cooking related UFP concentrations but can lead to domestic heat loss: this represents an IAQ and energy efficiency dichotomy. In this study a specialist test facility is used to explore this dichotomy during short-duration cooking activities replicated under different ventilation scenarios**, both related to natural and mechanical ventilation in the kitchen, and the relationship between ventilation and airflow around the home more generally**. We relate our results to the recently introduced World Health Organization (WHO) good practice statement on UFPs to determine good IAQ. Energy penalties associated with heat loss are calculated to determine which combinations of behavioural and technological interventions can best balance the competing demands of good IAQ and energy efficiency. It was seen that IAQ benefits were achieved at little detriment to energy efficiency. For natural ventilation, behavioural interventions such as opening windows for 20 minutes yielded significant IAQ benefits**, reducing UFPs from peak values by 86%.** Similarly, 20 minutes of mechanical extract ventilation operation yielded IAQ benefits, **reducing UFPs from peak values by 94%. However, in all ventilation scenarios UFPs remained above the WHO good practice high**

threshold for ~1 hour. All mechanical extract ventilation scenarios resulted in lower energy penalties than for natural ventilation. Our experiments also show that **airflow within the house is important to consider when looking at the IAQ and energy efficiency dichotomy.** Whilst results are primarily concerned with managing IAQ and energy efficiency under domestic cooking scenarios, there are wider implications for balancing IAQ and energy efficiency, which have increasing importance in light of management of the COVID-19 and energy crises and future policy, such as the Future Homes Standard.

Keywords: indoor air quality, ultrafine particles, cooking, ventilation, heat loss, energy efficiency

1. Introduction

The COVID-19 and global energy crises have thrust the challenges of managing buildings back into the limelight. A principal challenge pertains to promoting buildings that are conducive to occupant health and wellbeing, and that meet environmental targets associated with greenhouse gas emissions and energy efficiency. This tension typically manifests as a dichotomy between managing indoor air quality (IAQ) and energy efficiency: in particular through enacting appropriate ventilation strategies. Through the introduction and circulation of outdoor air to remove or dilute contaminated indoor air, ventilation can promote good IAQ. However, it makes up a sizeable proportion of the energy consumption in buildings through ventilation-related heat loss (Dimitroulopoulou, 2012; Guyot et al., 2018).

Decarbonising the UK building stock is a core part of the UK Government's Net Zero Strategy (HM Government, 2021b). In 2021, domestic environments were responsible for ~16% of greenhouse gas emissions (HM Government, 2023), and a range of different technologies and practices are suggested to achieve Net Zero buildings, including the wider use of insulation to reduce heat loss (HM Government, 2021a). Improved insulation in the UK's building stock will make dwellings more airtight and thus reduce the amount of energy required for heating. However, with improved rates of insulation there is the potential for increased accumulation of indoor generated pollutants (Petrou et al., 2022). Standards for acceptable ventilation rates are included in Part F of the Building Regulations (HM Government, 2010), though these have primarily been designed with a focus on energy efficiency rather than IAQ. During the COVID-19 pandemic the critical role of IAQ in influencing human health was brought to light (Settimo and Avino, 2021), and subsequently there has been a renewed focus on the role of ventilation in reducing exposure to poor IAQ, both for biological agents like SARS-CoV-2, but equally for other indoor air pollutants. Actions to improve IAQ, made necessary by the spread of COVID-19, have led to an increase in manual air changes (opening of windows) in order to dilute pollutant concentrations and reduce indoor exposures (Settimo and Avino, 2021). IAQ should be a priority in the design of buildings (Coggins et al., 2022), and focus is needed to ensure that energy efficiency interventions are administered with IAQ equally in mind (Settimo and Avino, 2021). With more individuals choosing to adopt hybrid or remote working practices, indoor air pollution exposures in the domestic environment will have an even greater impact on health and wellbeing (Coggins et al., 2022). While this paper is focussed on the retrofit and existing building sectors, it is clear that substantial efforts to increase airtightness in new homes in the UK are underway. This is indicated in a recent wide-ranging consultation about the future of new build homes which shall come into force in 2025 (HM Government, 2021c). New building regulations require an air permeability figure of up to 10 ($m^3/m^2.h$ at 50Pa) (HM Government, 2024), but with good practice placing this figure at 5 ($m^3/m^2.h$ at 50Pa). The Future Homes Standard consultation presents two options; one to keep the air permeability at 5 ($m^3/m^2.h$ at 50Pa) with intermittent mechanical extract ventilation, and natural ventilation, the second option is to reduce the air permeability to 4 ($m^3/m^2.h$ at 50Pa) with a continuous mechanical extract system. The latter of these options will have a pronounced effect on possible IAQ through increasing the airtightness.

The effects of poor IAQ on public health are becoming better understood. Globally, illness from poor IAQ results in over five million premature deaths every year, multi-million dollar losses due to reduced employer productivity, and increased health system expenses (González-Martín et al., 2021). While the majority of these premature deaths are occurring in low- and middle-income countries (World Health

Organization, 2014), poor IAQ is still a significant concern in high-income countries. Many unknowns remain, especially in domestic environments. This is in part due to the general lack of IAQ data, and a limited capability to monitor and predict spatial and temporal trends over time (Air Quality Expert Group, 2018): currently, evidence of domestic IAQ largely comes from individual research studies in specific settings, which measure different indoor air pollutants (Air Quality Expert Group, 2022). It follows that standards for acceptable concentrations of indoor air pollutants are less well defined than for outdoors. Regulations and guidelines affecting IAQ come from a wide range of sources which are not as well understood nor effectively implemented (Air Quality Expert Group, 2018). Moreover, advisory health-based guideline values on selected indoor air pollutants issued by the WHO and the United Kingdom Health Security Agency (UKHSA) have no statutory underpinning (Air Quality Expert Group, 2018).

The IAQ and energy efficiency dichotomy is acutely felt in domestic environments. Domestic environments have significant sources of indoor air pollution, including ingress of outdoor air, human activities (such as cooking and cleaning), building construction materials, and furnishings (Bekö et al., 2020). Cooking is conducted on an almost daily basis in most residences (O'Leary et al., 2019a), and is a major source of domestic indoor air pollution (Farmer et al., 2019; Logue and Singer, 2014; Patel et al., 2020), generating significant amounts of particulate matter (PM) and gaseous pollutants (Lai and Ho, 2008; Laverge et al., 2011). Researchers have investigated cooking emissions in real-world environments, where emissions are influenced by many factors (including room arrangement, building materials, outdoor infiltration, other combustion devices, ventilation, and cooking methods), and in controlled chambers, where there are fewer external influences and emissions are largely influenced by the type of fuel and the type of food being cooked (Huboyo et al., 2011). Reported emission rates for the cooking of single ingredients (Afshari et al., 2005; Dennekamp et al., 2001; Isaxon et al., 2015; O'Leary et al., 2019a; Wallace and Ott, 2011) and full meals (He et al., 2005) are highly variable. In the HOMEChem study, cooking activities were the primary source of indoor submicron particles. During cooking events, large enhancements in particle mass occur, with a substantial fraction of these increases due to chemical species related to cooking oils, and by number, these cooking associated particles were predominantly in the ultrafine mode (Farmer et al., 2019; Patel et al., 2020). Similarly, in a study by Shen et al (Shen et al., 2021) the predominant indoor pollutant source was cooking, leading to occasional high $PM_{2.5}$ spikes and differences between rooms dependent upon pathway distances from sources.

Cooking elevates concentrations of ultrafine particles (UFPs), particles which have a diameter ≤100 nm, the measurement of which has been the focus of many studies (Dennekamp et al., 2001; Xiang et al., 2021; Zhang et al., 2010). An approach to focus on monitoring of UFPs is chosen since most particles generated by cooking are within the ultrafine and fine particle size ranges (Abdullahi et al., 2013) and from an epidemiological perspective, these particles may exert higher toxicity (Ohlwein et al., 2019) causing more detrimental health effects. At present there are no air quality standards for UFPs anywhere in the world (Air Quality Expert Group, 2018). However, the WHO have recently introduced a good practice statement to distinguish between high and low ambient UFP concentrations, recognising their significant effects on health (World Health Organization, 2021).

Ventilation is the primary method of reducing cooking-related PM exposure, whether by mechanical extract ventilation, with in-built ventilation and/or fume extraction systems, or natural ventilation through window opening. Mechanical extract ventilation has been seen to have an important role in providing clean air in more energy efficient, airtight, retrofitted buildings (Coggins et al., 2022). Energy demand for ventilation has been quantified through looking at fan operation, and both the heating of supply air and air that infiltrates from the outside (Amanowicz et al., 2023). Ventilation energy challenges faced during the COVID-19 pandemic, a period with a sharp rise in ventilation energy use (Zheng et al., 2021) where energy efficiency became a secondary concern, are discussed in a systematic review (Moghadam et al., 2023).

Managing IAQ and energy efficiency in domestic buildings is critical to both promote health and well-being and meet Net Zero targets. However, a trade-off exists as increasing ventilation to improve IAQ undeniably requires more energy. **As one of the dominant sources of poor IAQ in the home, that**

typically occurs multiple times a day, with the potential for significant exposure to extend beyond the cooking environment, strategies to balance the IAQ-energy efficiency dichotomy during – and following – cooking are especially important. This dichotomy is understudied. Moreover, in a context where buildings are becoming more energy efficient, without careful consideration, there is the potential for IAQ to be exacerbated. This study aims to quantify energy efficiency and IAQ trade-offs through a series of discrete, short-duration cooking events in the kitchen of specialist test facility under different ventilation strategies and using high resolution IAQ monitoring equipment. UFPs are used as a proxy for IAQ, as they are a dominant indoor air pollutant arising from cooking activities, with potential significant health impacts which have been systematically under-reported: indeed, expanding the monitoring of UFPs has recently been recommended by the WHO (World Health Organization, 2021).

2. Materials and Methods

2.1. The Energy House

This study was based at The Energy House at the University of Salford, UK, which is a fully furnished two-bedroom end of terrace house, typical of Salford in 1919 (Ji et al., 2014). Numerous sensors in each room monitor a range of variables (including temperature, air flow velocity, boiler power and, energy usage) using a custom time series program to provide real-time analysis (Ji et al., 2014). The Energy House is located inside a climate-controlled chamber, which can replicate a wide range of weather conditions (Figure 1). In this study the chamber was set to 5.6 °C, typical of wintertime in the UK (Met Office, 2024), when the trade-offs between reducing cooking-related air pollution events and ventilation related heat loss are potentially at their greatest. **Thus, the chamber conditions can only be considered representative of those experienced during a calm day during winter.** The Energy House and Conditioning Void were maintained at the temperatures used by the UK Government's Standard Assessment Procedure (SAP) methodology for calculating domestic energy use of 21°C in the living room and 18°C in all other zones (BRE, 2021). Internal and external conditions were kept the same for the IAQ and ventilation rate measurements, which were conducted on different dates. **In practice, there are of course significant complexities in managing air quality across the indoor-**

outdoor interface, whereby efforts to remove indoor air pollution through increasing air change with the outdoors inevitably brings in outdoor air, which may also be polluted. However, for the purposes of this study, the use of the Salford Energy Houses' climate-controlled chamber allowed us to focus more specifically on isolating the impacts of cooking sources and ventilation on IAQ, and energy use.

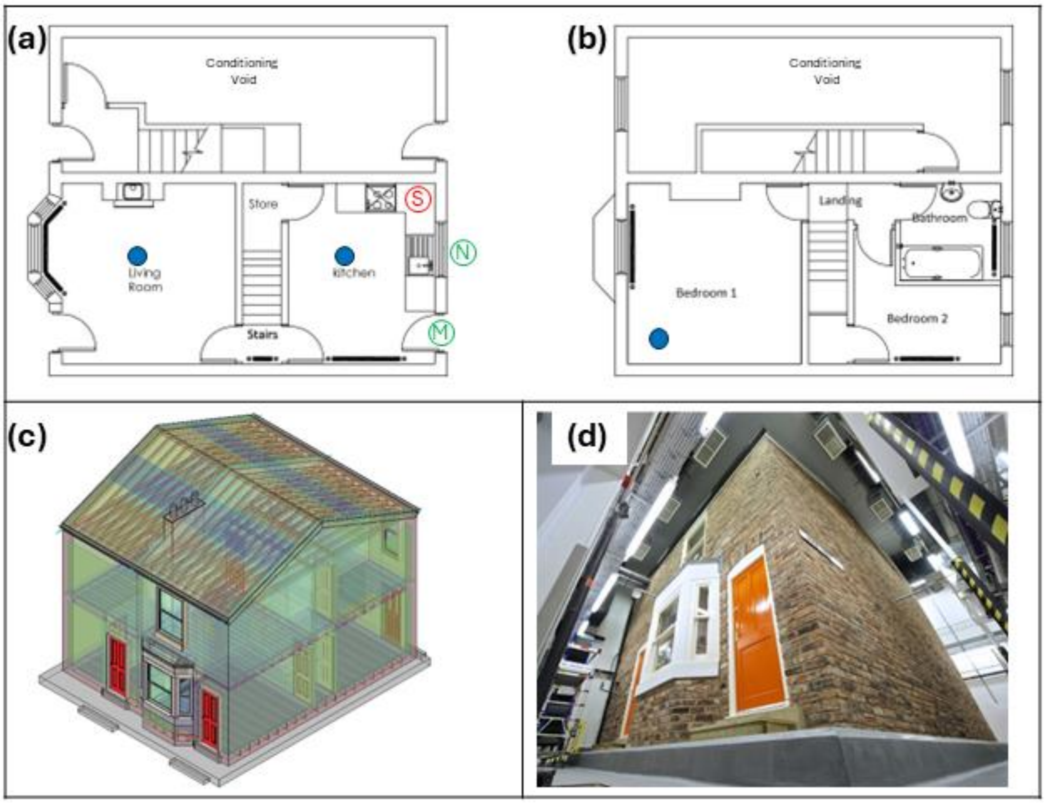

Figure 1: The Energy House floor plans showing (**a**) ground floor showing (S) the location of cooking activities, the location of the kitchen window (N) and (M) the location of the mechanical extract fan (**b**) first floor (**c**) the 3D Energy House model and (**d**) the Energy House in the chamber (Ji et al., 2014). Locations of IAQ monitors are shown with blue circles. The Conditioning Void attached to the house was used to replicate the typical indoor end-terrace environment.

2.2. Air quality measurements and experimental design

Most particles generated from cooking are UFPs (Farmer et al., 2019), which provides justification for their monitoring to determine occupant exposure to cooking-generated particles (Isaxon et al., 2015).

Particle number concentration (PNC) – the number of particles in a given volume of air – is commonly used for measuring UFPs as around 90% of the total PNC is in the UFP size range (Morawska et al., 2008). PNC was monitored at 1s intervals using the NAQTS V2000 (V2000), which has an in-built condensation particle counter (CPC) to measure PNC with a lower limit of 15 nm **(Gounaris et al.,** 2024)**, which is slightly higher than many CPCs which are < 10 nm. The CPC is housed** alongside an array of other air quality and environmental sensors ~~(Booker, 2024)~~ (Supplementary Information 1). Prior to deployment the three V2000s were co-located for calibration purposes. **One of the V2000s was ISO-27891 calibrated prior to the study and served as a reference unit to normalise the PNC response of the two other V2000s. The V2000s had a correlation coefficient of 0.89-0.90, and a slope between 0.83-0.88 to the reference unit using a 60 second rolling average.** They were then situated in different rooms in The Energy House (Figures 1a and 1b). Background PNCs were established and the V2000s were then used to capture PNC for three sets of cooking experiments (Table 1). In this paper measured PNCs are related to the WHO good practice statement on UFPs (World Health Organization, 2021), which designates concentrations greater than 20,000 particles per cm^3 over a 1-hour period as high.[1]

Expt.	Source	IAQ Monitors	Ventilation Type	Ventilation Period	Internal Doors
1a	Toast	1	None	-	Closed
1b	Toast	1	Natural	From completion of cooking (60 mins)	Closed
1c	Toast	1	Natural	From completion of cooking (20 mins)	Closed
1d	Toast	1	Natural	From completion of cooking (10 mins)	Closed
1e	Toast	1	Natural	From completion of cooking (05 mins)	Closed
2a	Fried Egg	1	None	-	Closed
2b	Fried Egg	1	Natural	From completion of cooking (60 mins)	Closed
2c	Fried Egg	1	Natural	From completion of cooking (20 mins)	Closed
2d	Fried Egg	1	Natural	From completion of cooking (10 mins)	Closed
2e	Fried Egg	1	Natural	From completion of cooking (05 mins)	Closed

[1] Note that the WHO good practice statement on UFPs suggests that measurements should be made with a lower limit of ≤ 10 nm. However, the V2000 has a lower limit of 15 nm. In practice, this means that we will be slightly under-reporting PNCs.

2f	Fried Egg	1	Mechanical	From onset of cooking	Closed
3a	Toast	3	None	From completion of cooking (60 mins)	Open
3b	Toast	3	Natural	From completion of cooking (20 mins)	Open
3c	Toast	3	Natural	From completion of cooking (05 mins)	Open

Table 1. Replicated cooking activities (toasting and frying) over the four consecutive days of monitoring at The Energy House. Further experimental details: number of IAQ monitors, ventilation type and duration, and housing configuration are given.

All cooking was conducted in the kitchen, in most instances with the internal door to the living room closed. Three consecutive sets of experiments were undertaken. In the first set, white bread was toasted for 5 minutes on the highest setting and the kitchen sash window was opened by 250 mm for different periods of time once cooking had ceased (Table 1). In the second set, a single egg was fried over an electric hob and the kitchen was naturally ventilated for the same time periods as described previously, plus for an additional mechanical extract ventilation scenario. Mechanical extract ventilation (using a Simply Silent DX150 intermittent extract fan mounted in the external doorframe) was used from the onset of cooking for 30 minutes. **Our ventilation approach was an attempt to mimic real-world practices of using ventilation, including 'shock' natural ventilation to remove indoor generated air pollution once cooking had completed, and mechanical ventilation for certain cooking activities.** The third set of experiments replicated toasting activities with internal doors in the Energy House open. This changed airflow throughout the house and subsequently opportunities for dispersion and deposition of UFPs. Before each individual experiment, the pans and cooking utensils were cleaned in warm water and hand dried. At the end of each frying event, the hob was turned off and a lid was placed over the frying pan to prevent continued emissions, using a similar protocol to O'Leary et al. (O'Leary et al., 2019a).

2.3. Ventilation rate measurements

The ventilation rate of the kitchen in air changes per hour (AC/H) was measured using the tracer gas decay method outlined in ASTM E741-11 (2017). CO_2 was released into the kitchen with the window in the closed and open positions and all internal doors closed. CO_2 concentration measurements were taken at the centre of the kitchen at 30s intervals using a Sauermann Si-AQ Expert IAQ monitor (Si-AQ) (uncertainty ± 2% reading or ± 10 ppm), for each natural ventilation scenario (Supplementary Information 2). These measurements were conducted independent of the cooking experiments as the ventilation periods associated with these experiments were deemed too short to obtain robust measurements of AC/H. A ventilation period of one hour in duration was used to undertake the CO_2 decay measurements. A TSI / Airflow PH731 electronic balometer (± 3% reading and ± 4 l/s) was used to measure the extract rate of the mechanical ventilation system.

2.4. Kitchen heat load measurements

The steady state space heating requirement of the kitchen in Watts (W) at 5.6 °C external temperature was measured prior to the ventilation rate measurements. Electric resistance heaters with thermostatic controllers maintained SAP internal temperatures in each zone of the Energy House and Conditioning Void. Conditioning of the internal and external environments commenced 48 hours prior to the measurements so that heat transfer between the internal environment of the Energy House and the chamber was considered akin to steady state (Farmer et al., 2017). Fibaro smart wall plugs (uncertainty ± 1%) were used to measure the space heating power input for each zone. Time constraints meant that it was only possible to accurately measure space heating power requirements without additional ventilation provision.

2.5. Calculating energy penalties

This study considers increases in energy consumption attributable to space heating demand and the operation of natural and mechanical extract ventilation systems. Energy penalties are defined as the additional energy consumption required to maintain the internal setpoint temperature during periods of increased ventilation to improve the IAQ. These energy penalties were calculated using the energy required to heat additional air change with the external environment based on the ventilation rate measurements.

2.5.1. Natural Ventilation

The energy penalty for a window opening ventilation period was obtained using the following equation.

$$E_p = (E_h - E_c) + E_v$$

Where:

E_p= Energy penalty that includes additional heat input from cooking appliance

E_h = Energy required to maintain kitchen air temperature with window closed (obtained from energy measurements with the Energy House at steady state (Section 2.4))

E_c = Heating energy input from cooking device during cooking period

E_v = Energy required to heat additional air infiltration required for cooking ventilation (obtained from ventilation rate measurements)

E_v is calculated as;

$$E_v = \frac{\Delta n \, c_p \, \rho \, V \, \Delta T \, t_v}{3600 * 1000}$$

Where:

Δn is the measured increase in the air change rate within the ventilated space[2] (ACH)

c_p is the specific heat of air[3] (J/kg K)

ρ is the density of air[4] (kg/m^3)

V is the volume of the ventilated space[5] (m^3)

ΔT is the temperature difference between the set-point temperature and external environment (K)

t_v is the ventilation period (hours)

2.5.2. Mechanical Extract Ventilation

[2] The 3600 value in the denominator accounts for the conversion of ACH to ACS and the 1000 value converts Wh to kWh.
[3] Specific heat of air at 5°C is 1002 J/kg K (Engineering Toolbox, 2020)
[4] Density of air at 5°C is 1.268 kg/m^3 (Engineering Toolbox, 2020)
[5] Volume of kitchen is 26.92 m^3

The energy penalty for a mechanical extract ventilation period was obtained using the following equation.

$$E_p = (E_h - E_c) + E_v + E_f$$

Where:

E_v = Energy required to heat additional air infiltration required for cooking ventilation (obtained grille flow measurement of extractor fan)

E_f = Energy required for mechanical ventilation over operational period (based on manufacturers literature value of 22.6 W)

3. Results

In this section we first present the PNC results under the different ventilation scenarios (none, natural and mechanical) before presenting energy penalty calculations. The IAQ and energy efficiency dichotomy is explored in the discussion section that follows.

3.1. Indoor Air Quality

3.1.1. Kitchen only (Experiments 1 & 2)

PNC profiles generated by the discrete cooking episodes exhibit similar trends (Figure 2a, 2b). PNC are initially low then increase rapidly over time as cooking progresses, indicating ongoing emissions of UFPs until a peak concentration is reached. Once cooking has stopped, the PNC decays exponentially towards background concentrations with the rate largely governed by the AC/H.

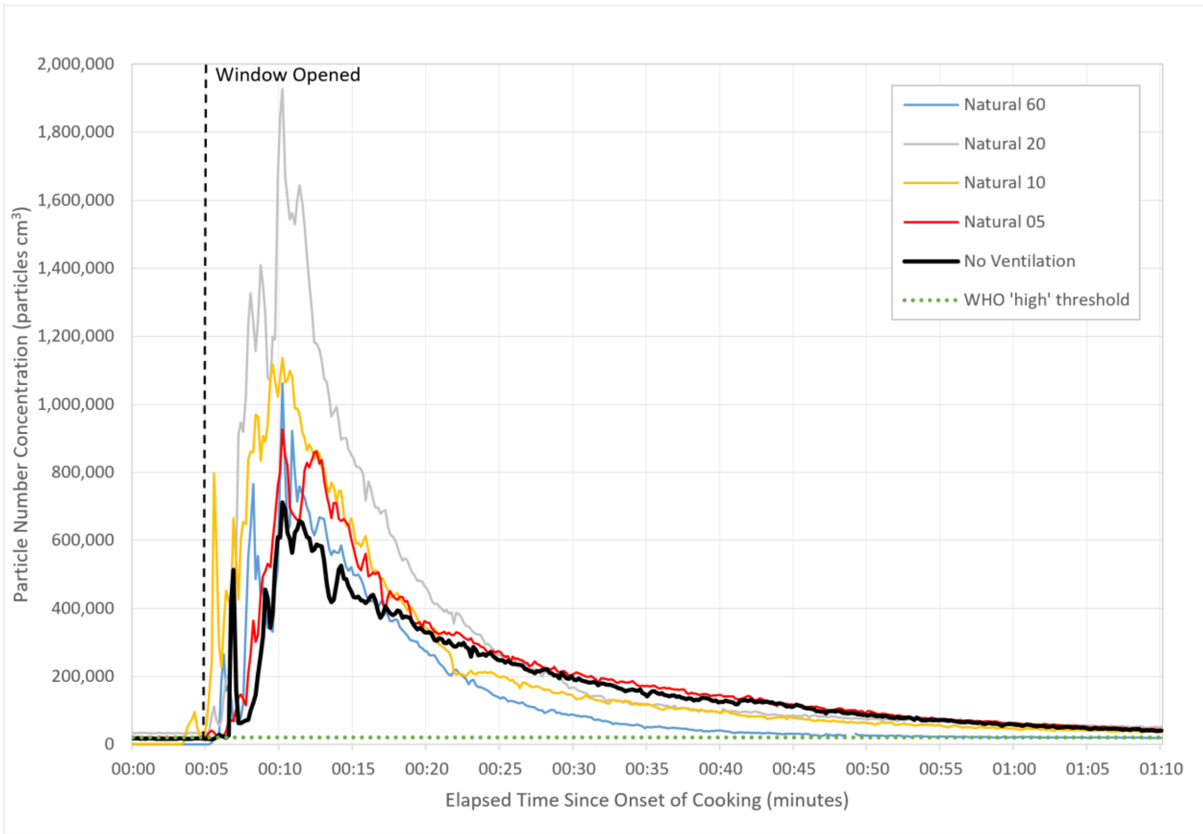

Figure 2a: PNC resulting from cooking toast under different ventilation scenarios. See Table 1 for details of individual experiments and ventilation scenarios corresponding to each scenario.

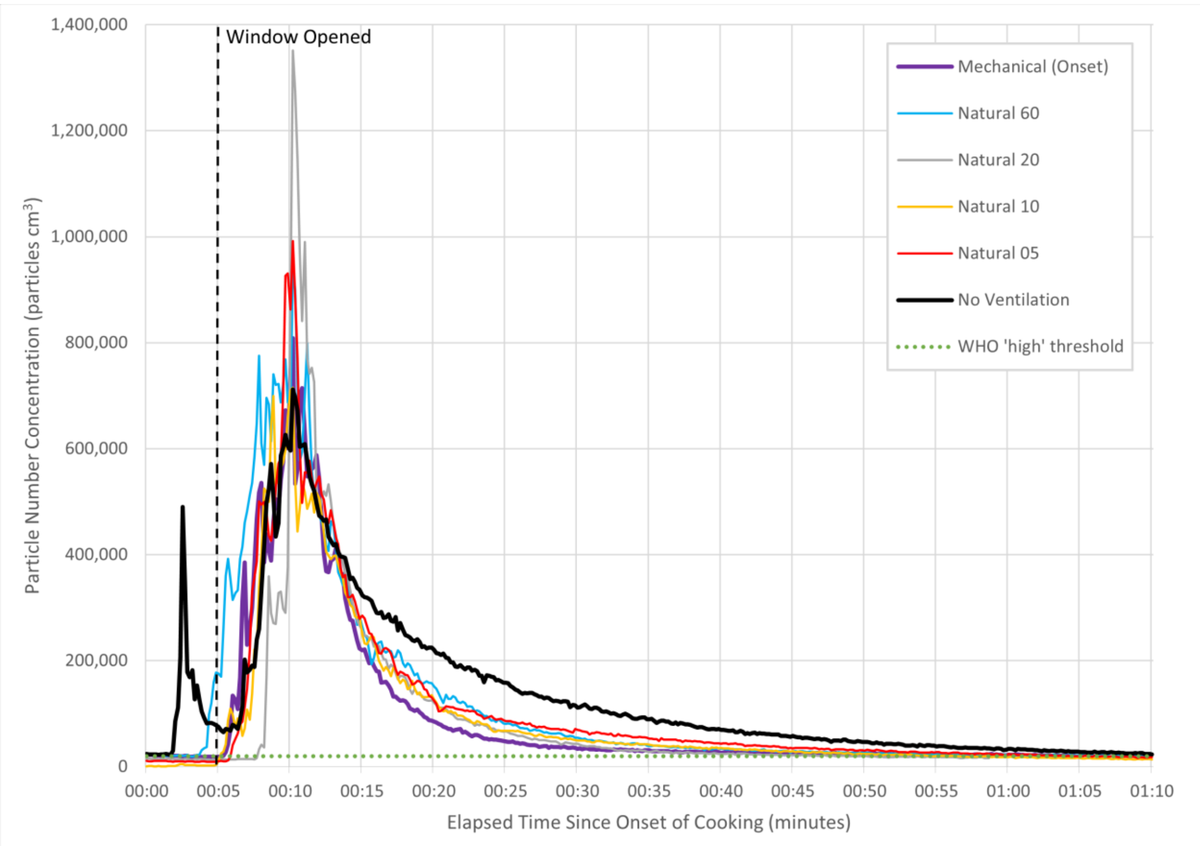

Figure 2b: PNC resulting from frying eggs under different ventilation scenarios. See Table 1 for details of individual experiments and ventilation scenarios corresponding to each scenario.

The PNC profiles highlight significant differences between ventilation scenarios. Peak PNC differed between experiments, reflecting variations in source strength, which had a consequential effect on the time to reduce PNC below the 'high' threshold designated in the WHO good practice statement on UFPs. Ventilation rate is perceived as the dominant force controlling PNC decay.

The rate of decay from peak to background PNC is similar in most scenarios, with the non-ventilated scenarios (Table 1: 1a, 2a) exhibiting slower rates of decay due to reduced AC/H. In ~~some of~~ the ventilated scenarios a higher initial decay rate (first 20 minutes) relative to the subsequent and overall average decay period is observed. The initial decay rate is likely to be dominated by dispersion (promoted by ventilation), whilst other processes, such as deposition are more likely to explain the subsequent slower decline to background levels. It was hypothesised that opening the window for the longest period would elicit the fastest decay rate due to greater AC/H between the kitchen and the chamber. This statement holds true for toasting, and most frying cases. Results for frying based on assessment of decay rates and PNC profiles (Figure 1, Figure 2) suggest mechanical extract ventilation is the most effective mitigation strategy to improve IAQ. This is particularly evident during the higher initial decay rates (first 20 minutes). Based on decay rates, Scenarios 1b (natural ventilation, 60 minutes) and 2f (mechanical extract ventilation) (Table 1) are most effective after toasting and during frying, respectively, **reducing PNC from peak values by 86% and 94% respectively after 20 minutes of ventilation.** ~~for improving IAQ and reducing potential exposures to UFPs.~~

3.1.2. Whole house (Experiment 3)

PNC data from one near-field (kitchen) V2000 monitor and two far-field (living room and upstairs) V2000 monitors reveal further information about the relationship between ventilation and airflow around the Energy House (Figure 3). Though much lower than in the kitchen, high PNC in other regions of the house, especially the living room, suggest internal transfer of UFPs despite the kitchen window being open and the internal doors being closed. When the kitchen window is open and the internal doors are open, PNC are much lower in the kitchen where the source is located, but much higher in the adjacent living room and upstairs bedroom (Figure 1), with PNC remaining above background levels for longer periods of time. This suggests that to understand indoor exposure to UFPs it is equally as important to consider air changes between rooms as it is between the kitchen and external chamber.

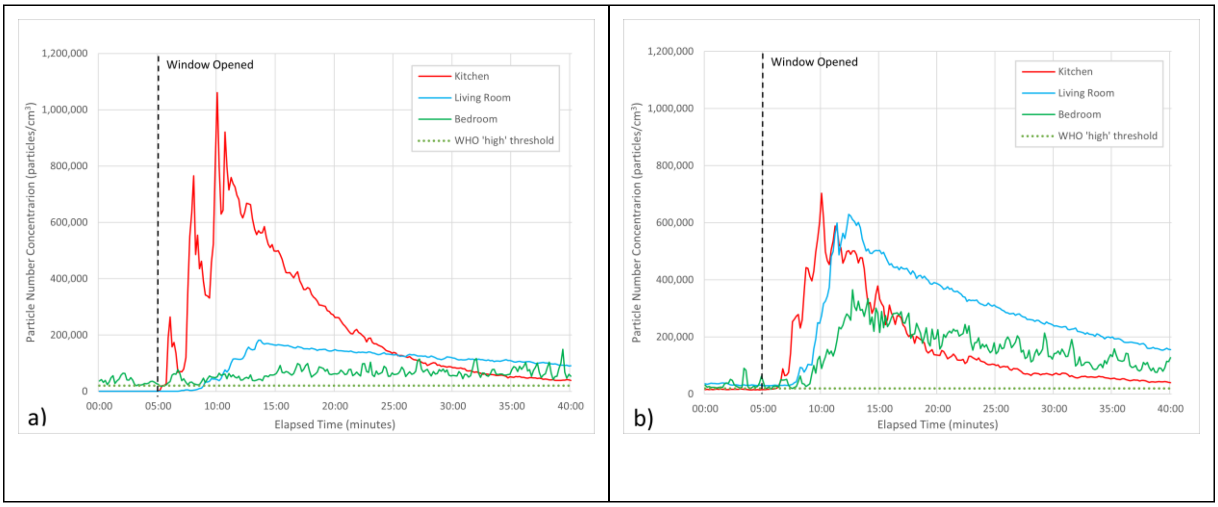

Figure 3: Times-series of PNC recorded in both near-field (kitchen) and far-field (living room and bedroom) locations as a resulting of toasting under naturally ventilated conditions with internal doors (a) closed and (b) open.

3.2. Energy Penalties

As stated previously, an energy penalty is defined as additional energy consumption resulting from actions undertaken to improve IAQ by reducing the concentration of cooking generated UFPs. Measured AC/H were used to estimate additional ventilation heat loss and energy required to heat incoming air for periods of ventilation at 5.6 °C external temperature. Following this, the heat gains associated with the cooking process and its influence on space heating demand were considered.

3.2.1. Ventilation heat loss

Ventilation rate measurements and the energy required to heat the incoming air for different periods of ventilation, without considering additional heat inputs from cooking is shown in Table 2. The electrical power demand of the mechanical extract ventilation system (23 W) is included within the values for heating incoming air in this scenario.

Ventilation	n (ACH)	Ventilation heat loss (W)	Energy required to heat exchanged air (kWh)				
			60 mins	30 mins	20 mins	10 mins	5 mins
Background	2.3	293	0.293	0.146	0.097	0.050	0.023
Window open	7.5	962	0.962	0.481	0.317	0.164	0.077
Extract on	7.0	888	0.911	0.455	0.301	0.155	0.073
Δwindow	5.2	669	0.669	0.335	0.221	0.114	0.054
Δextract	4.7	596	0.618	0.309	0.204	0.105	0.049

Table 2: Air change rates, ventilation heat loss rates, and energy required to heat air exchanged during each ventilation period for the cooking scenarios.

The measured ventilation rate with the kitchen window closed was 2.3 AC/H. This implies that the house is hard-to-treat in terms of energy efficiency and may incur higher rates of infiltration than newer housing stock (Ji et al., 2014). **The high AC/H can be attributed to the high air permeability value of 15.7 $m^3.h^{-1}.m^{-2}$ @ 50 Pa when the Energy House is fitted with single glazed timber sash windows: this value is 37% greater than the UK average air permeability value of 11.5 $m^3.h^{-1}.m^{-2}$ @ 50 Pa for homes constructed before 1998 (Stephen, 1998).** The ventilation rate increased by 3.3 times and 3.0 times for window opening and extract ventilation, respectively. This suggests that both measures provide similar levels of additional ventilation. However, it must be noted that the sheltered conditions in the Energy House chamber mean that measurements for window opening may only be experienced on calm days in the real-world. The increase in ventilation rate achieved by mechanical extract will be less influenced by external environmental conditions.

The increase in energy associated with ventilation was 3.3 times greater with the window open and 3.1 times greater with mechanical extract ventilation than background ventilation. The mismatch between increases in ventilation rate and energy requirement for mechanical extract ventilation is due the energy consumption of the fan, which accounted for four percent of the increased energy requirement.

3.2.2. Energy Penalty including cooking gains.

The increase in ventilation *heat loss* should be considered alongside the *heat gain* associated with each cooking activity. The energy penalty (E_p) considers heat generated by the cooking processes. In this case the power outputs of the toaster and hob were 1200 W and 1700 W respectively. The power input from each cooking appliance far exceeds the measured steady state rate of heat loss from the kitchen with no additional ventilation of 635 W (this includes fabric and ventilation heat losses). Additional heat input from appliance use will result in a rise in kitchen temperature (under certain circumstances) and could result in overheating, necessitating the requirement for additional ventilation to maintain thermal comfort as well as good IAQ. The calculations assume the toaster is operational for three minutes and the hob for eight minutes (comprises three minutes to heat hob and pan and five minutes cooking time).

When considering the additional heat input from the cooking processes, lower energy penalties are observed likely attributed to lower ventilation heat losses (Table 3). It is observed that more heat can be generated from frying than is lost by additional ventilation heat loss for a 5- or 10- minute period, so an energy surplus is observed (shown as negative numbers in Table 3). In all instances of toasting, an energy penalty is observed, since less energy is generated, but this is negligible for 5- and 10- minute periods of window opening which are insufficient to reduce PNC to below the high threshold designated in the WHO good practice statement on UFPs. For extended periods of natural ventilation, more heat is lost through ventilation than gained through the cooking processes hence the generation of higher energy penalties. When periods of natural ventilation extend beyond 20-minutes, larger energy penalties occur, even when considering the energy generated by cooking activities, due to prolonged periods of air change with the cooler air of the chamber.

Cooking Activity	Ventilation	Energy penalty for ventilation period (kWh)					
		60 mins	30 mins	20 mins	10 mins	5 mins	No Ventilation
Toasting	Window	0.641	0.306	0.193	0.089	0.025	-0.028
Frying	Window	0.531	0.196	0.082	-0.025	-0.085	-0.138
Frying	Mechanical	0.618	0.309	0.204	0.105	0.049	-0.138

Table 3: Energy Penalty (E_p) based on differing ventilation periods for toasting and frying under test conditions.

Energy penalties required to meet the WHO good practice statement on UFPs high threshold (hourly average of less than 20,000 particles per cm^3) will vary across the year. Given the short period of time for cooking scenarios and PNC decays, PNC values often did not drop below the high threshold in our experiments. Therefore, AC/H were calculated using PNC decay curves to allow us to extrapolate decay data to characterise the length of time required to go below the high threshold. For example, on a typical winter day at the Energy House, achieving an hourly average of less than 20,000 particles per cm^3 following the frying of an egg would require a 0.49 h period of window opening, resulting in an increase in ventilation heat loss of 0.328 kWh (excluding cooking gains) and energy penalty of 0.189 kWh. It is important to note that energy penalties will vary depending upon external conditions (Figure 4). For example, the energy penalty at the Energy House for an average December day would be 12 times greater than that in May.

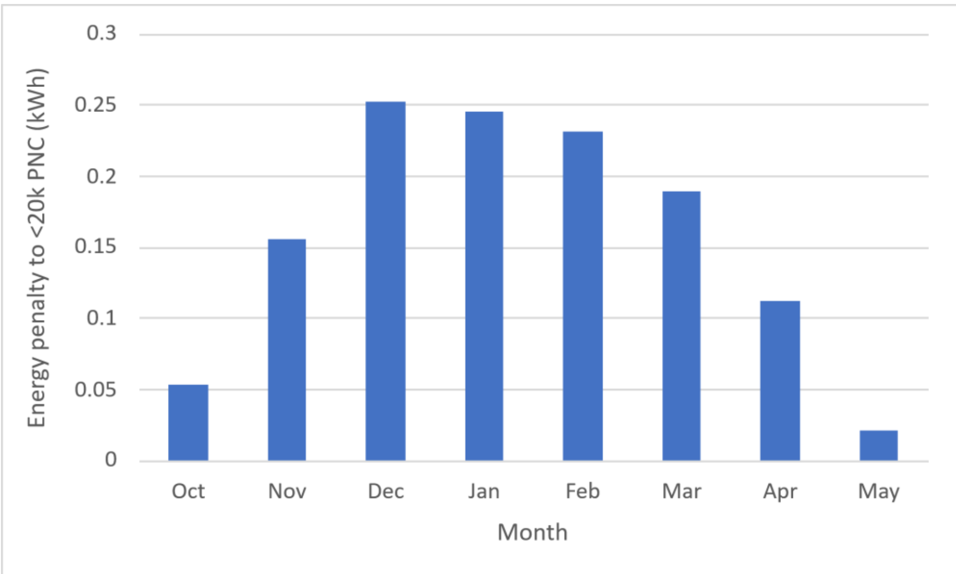

Figure 4: Energy penalty per frying event at the Energy House during each month of the SAP heating season.

4. Discussion

In this study domestic cooking, which is conducted daily in most homes, generated significant UFP concentrations (which we measured as PNC). Since eliminating this source of poor IAQ is neither possible nor desirable, effective mitigation through ventilation is essential to ensure good IAQ and protect the health and well-being of occupants (Singer et al., 2012). Whilst infiltration alone is typically not sufficient to dilute PNC (O'Leary et al., 2018), the higher AC/H (2.3) of the "leaky" Energy House can reduce PNC to some degree, albeit not as effectively as purpose-provided ventilation, in either natural or mechanical extract form. When windows are opened, the AC/H increases from 2.3 to 7.5, and a more rapid and significant reduction in UFP concentrations is observed. Window opening has a more significant effect of reducing the PNC for the first 20 minutes, observed through higher initial decay rates.

Whilst energy penalties are not associated with non-ventilated scenarios, the IAQ penalty is considerable. In the hour during and following cooking experiments the PNC is 5-10 times greater than the UFP concentrations that the WHO regards as high. This IAQ penalty persists for over an hour before UFP concentrations return to background, below the WHO good practice statement on UFPs high threshold of 20,000 per cm^3 over a 1-hour period. Some ventilation is clearly better than no ventilation to increase the rate of removal of internally generated UFPs, however, there are clear energy penalties associated with ventilation. If we *exclude* the energy inputs associated with cooking, the energy penalties are modest and increase over time with extended periods of natural ventilation. If we *include* the heat generated through cooking, the energy penalties associated with natural ventilation are negligible, particularly in the case of frying activities, due to the greater heat input associated with this activity. ~~Figure 5 illustrates these trade-offs for all cooking experiments in schematic form.~~ In this specific study we identified an initial 20-minute window during which IAQ improvements can be achieved with no energy penalties. However, these IAQ improvements do not result in UFP concentrations below the WHO ‘high’ UFPs threshold. Achieving this threshold requires longer periods of ventilation and subsequent energy penalties.

Mechanical extract ventilation can reduce PNC more rapidly than natural ventilation (Figure 2), despite having a slightly lower AC/H. The rate of ventilation is also more consistent when mechanically driven. The first 20 minutes appear to be the most significant for reducing UFPs and only modest energy penalties were incurred during this period. This leads us to conclude that this initial 20-minute period of mechanical extract ventilation after cooking represents the ideal time to balance the dual objectives of good IAQ and energy efficiency. Energy penalties will increase for longer periods of ventilation, whether natural or mechanical.

Our findings are consistent to those reported in Dobbin et al. (Dobbin et al., 2018) and O’Leary et al. (O'Leary et al., 2019b) where exposure to UFPs and $PM_{2.5}$ was reduced by continuing to ventilate for 10–15 minutes after cooking. These papers acknowledge the trade-offs in long-term mechanical extract ventilation, including the noise generated and energy used, and the impracticalities for use for long periods after cooking (O'Leary et al., 2019b). Therefore, these represent timings where mechanical extract ventilation incurs only a small cost (e.g., heat loss) while the IAQ benefits are considerable. O’Leary et al. (O'Leary et al., 2019b) similarly showed $PM_{2.5}$ concentrations reduce by 58% for 10 minutes of extra ventilation after cooking ends when compared to ventilation during cooking alone. However, increasing the ventilation period to 15 minutes only reduces concentrations by a further 8% demonstrating a diminishing return on IAQ improvement through ventilation. This is akin to our previous finding about ventilating for over 20 minutes with window opening.

4.1. Future work

In this study energy efficiency and IAQ trade-offs were quantified through a series of short-duration cooking experiments in The Salford Energy House. There are clear opportunities to expand upon our findings.

A clear methodology that can be augmented to investigate the IAQ-energy efficiency dichotomy during cooking is outlined in this paper which can be applied to a range of different structural, behavioural, and environmental situations. Whilst the energy penalties observed are low on the order of a single short-duration experiment, they increase significantly when scaled up over a full heating season. Alongside this, further work could more comprehensively examine the effect of seasonality on energy penalties to exposure mitigation (Figure 4). It is anticipated that increased AC/H in the cooling season due to frequent window opening to moderate internal temperatures would promote faster rates of UFP removal. Likewise, higher outside temperatures would also result in lower energy penalties with less need for any temperature recovery in the indoor environment.

It is also important to note that our scaling is based on a single, short-lived cooking event per day, whereas in the 'real-world', cooking is often done sequentially (Farmer et al., 2019; Patel et al., 2020), and is shaped by a range of different cultural, and social factors, including different cuisines and cooking styles. Therefore, we would expect a more complex and varied set of relationships between IAQ and energy efficiency due to more complicated cooking and ventilation regimes. This complexity is of particular importance when characterising exposure to UFPs, as in our set of discrete experiments we were able to let concentrations return to near-background concentrations. However, in a real-world setting, with more frequent use of sources of UFPs, this would be more difficult. The implications of this are that occupants are likely to be exposed to high concentrations of UFPs (as designated by the WHO) for longer periods of time.

Likewise, future research could follow a similar methodology to examine trade-offs between IAQ and energy efficiency **in either test or real-world environments** across different segments of housing stock, **with differing atmospheric conditions that influence natural ventilation, outdoor air quality, and** with different mechanical extract ventilation systems ~~in either test or real-world environments (Farr, 2020)~~. **Importantly, future work needs to reflect ongoing increases to the airtightness of the UK housing stock, which will likely change how the IAQ-energy efficiency dichotomy manifests.** This work will be developed using two newly created test homes that have recently been built in the Energy House 2.0 test facility at the University of Salford. These homes closely resemble fabric and service provisions as suggested in the current Future Homes Standard (Richard Fitton, 2024a, b). Moreover, future research could evaluate the efficacy of supplementary air cleaning technologies in managing the IAQ-energy efficiency dichotomy (Lowther et al., 2023). **These devices can help to provide 'equivalent' air change rates in settings where ventilation is more difficult, as evidenced during COVID-19 (Morawska et al., 2024). There is a long history demonstrating the efficacy of HEPA filters in reducing indoor PM by ~30-80% (Kelly and Fussell, 2019). For example, Batterman et al. (Batterman et al., 2012) demonstrated an ~50% reduction in PM in low-income homes with asthmatic children. Likewise, Batterman et al. (Batterman et al., 2005) demonstrated 30-70% reductions in PM in homes with smokers. Moreover, the efficacy of using multiple HEPA filters around the home has been evaluated, with similar reductions in PM (Lowther et al., 2023). Alongside HEPA filters, there are a range of other emerging air cleaning technologies, such as UV irradiators and adsorption systems. However, the evidence on their reduction in PM is less clear than for HEPA (Booker et al., 2025)**.

This study also illustrated that activities in one indoor location (e.g. cooking in the kitchen) had significant impacts on IAQ across the house. This characterisation is important to develop models of personal exposure in indoor environments. For example, occupants are not just exposed to cooking related UFPs in the kitchen but can also be exposed to concentrations greater than the WHO high threshold in bedrooms overnight. This outlines both that pollutants migrate around the domestic environment, but also that additional ventilation in other rooms may be essential to reduce exposure. Moreover, to balance the conflicting objectives of minimising energy consumption and maximising IAQ, ventilation systems must be modernised, shifting from space-based designs to occupant-based designs in domestic environments (Amanowicz et al., 2023; Moghadam et al., 2023), which can better adjust to occupant needs. Guyot et al. (Guyot et al., 2018) have shown that significant energy savings of up to 60% can be obtained without compromising IAQ with demand-controlled ventilation due to a lower demand for ventilation airflow and thus a lower amount of energy to drive fans.

5. Conclusion

This study investigated the trade-offs between the dual objectives of good IAQ and energy efficiency. Through conducting a series of short-duration discrete cooking activities in a specialised test facility, energy penalties associated with reducing UFPs were characterised under different ventilation scenarios.

This study in the Energy House has shown that improvements in IAQ can be made with no energy penalties for short periods of time up to 20 minutes. Both natural and mechanical extract forms of ventilation can lead to substantial reductions in UFP concentrations during this window, with mechanical extract ventilation being particularly effective. However, ventilation needs to extend beyond 20 minutes for UFP concentrations to drop below the WHO high threshold for UFPs, and energy penalties are incurred as a consequence. Therefore, a clear balancing of the dichotomy can be achieved over shorter periods of time, but it remains problematic over a longer period of time. Nonetheless, ventilation for up to 20 minutes after a cooking event may be a reasonable suggestion and potentially memorable making it appropriate to encourage behaviour change.

Over the past few decades building management and research has been largely focused on promoting energy efficiency resulting in the unintended consequence of an IAQ and energy efficiency dichotomy. The emergence of COVID-19 has interrupted this balance by encouraging substantially increased ventilation rates to improve IAQ at the expense of energy efficiency. However, ventilation practices to manage COVID-19 are now being balanced against other contemporary issues including the ongoing energy crisis and plans to meet UK Net Zero targets. These competing factors highlight the continued importance of managing tensions between IAQ and energy efficiency.

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Quantifying the trade-offs between indoor air quality and energy efficiency in a specialised test facility

Frederiksen C, et al. 2025 I *Atmospheric Environment*

Domestic cooking contributes to poor indoor air quality (IAQ)

Increasing ventilation rates improves IAQ, but may lead to domestic heat loss

Study recommendations have wider implications in light of global energy crises

Short duration cooking activities *replicated under* ***different ventilation scenarios***

Ultrafine particle (UFP) concentrations *monitored with V2000 units*

Relate to ***World Health Organization (WHO) good practice statement for UFP***

Energy penalties *consider increase in energy consumption associated with space heating demand and operation of ventilation systems*

NAQTS V2000

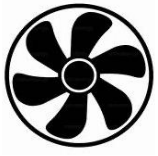
Salford Energy House

UFP Concentrations and Energy Implications

UFPs above WHO good practice guidelines for ~1 hour. After 20 min:

Reduced UFPs by **86%**

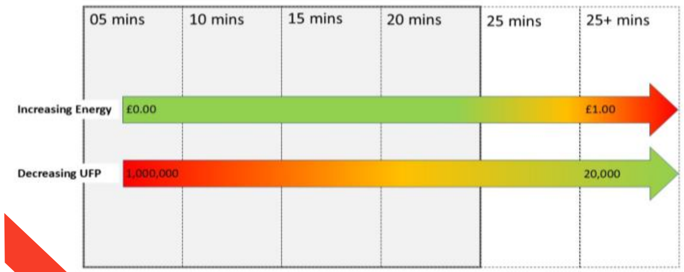
Energy penalty ***0.082-0.193*** *kWh which increases with ventilation time*



Reduced UFPs by **94%**

Energy penalty ***0.204*** *kWh which increases with ventilation time*

Illustrative trade-offs between IAQ and energy efficiency



IAQ can be **improved for up to 20 minutes after a cooking event through ventilation** before energy penalties are incurred

Figure 1 Click here to access/download;Figure;Figure 01.png

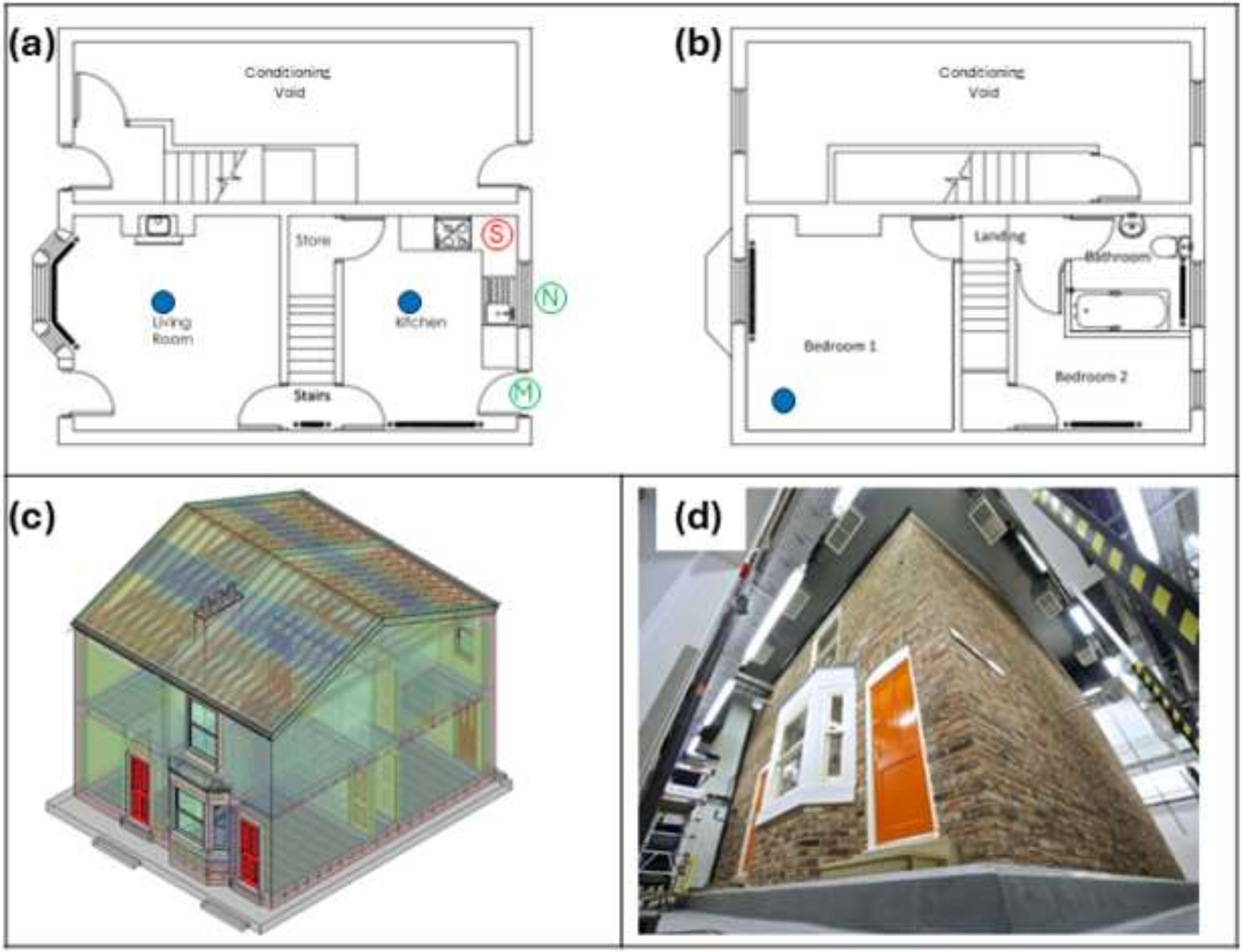


Figure 2a (revised)

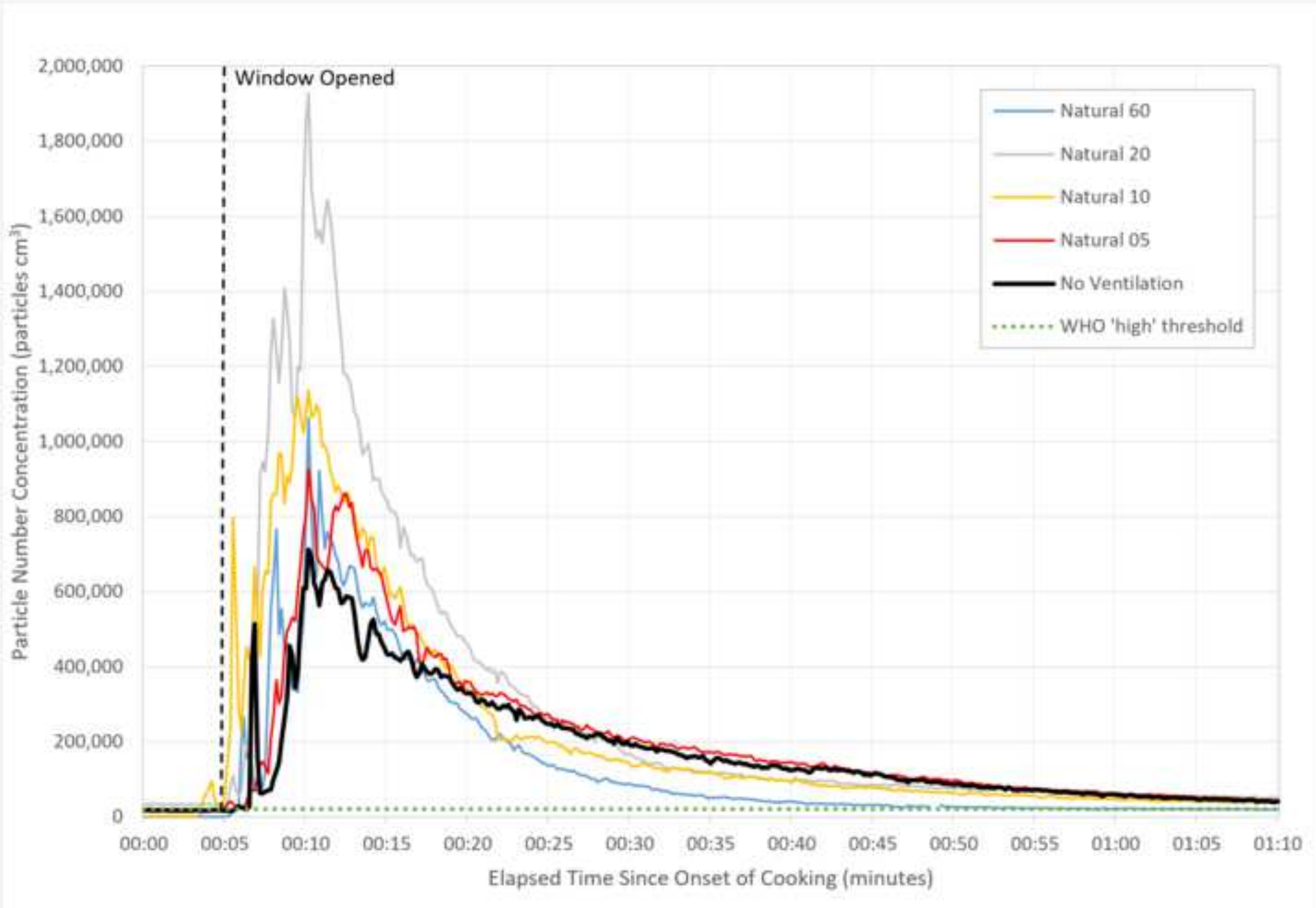


Figure 2b (revised)

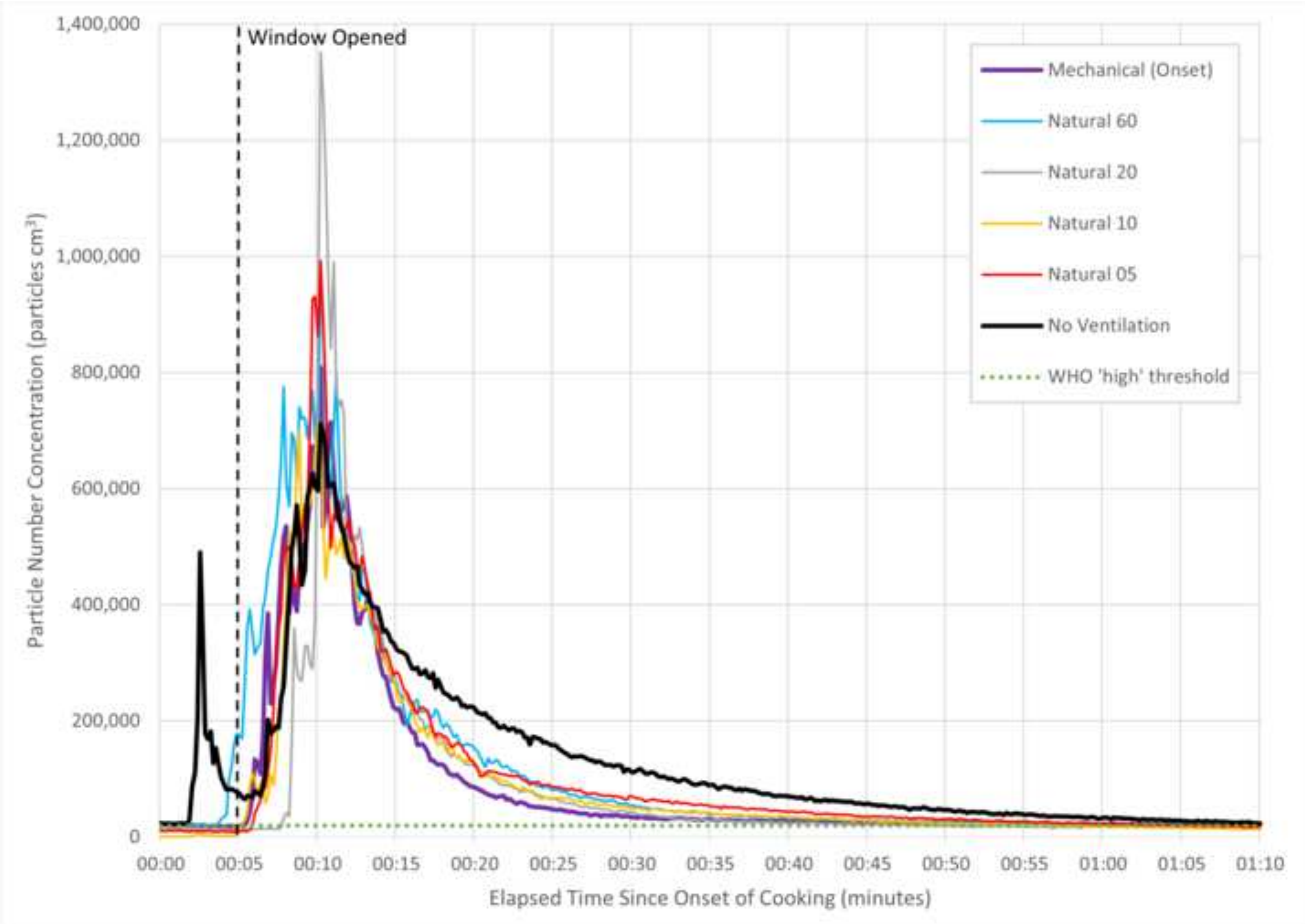


Figure 3a (revised)

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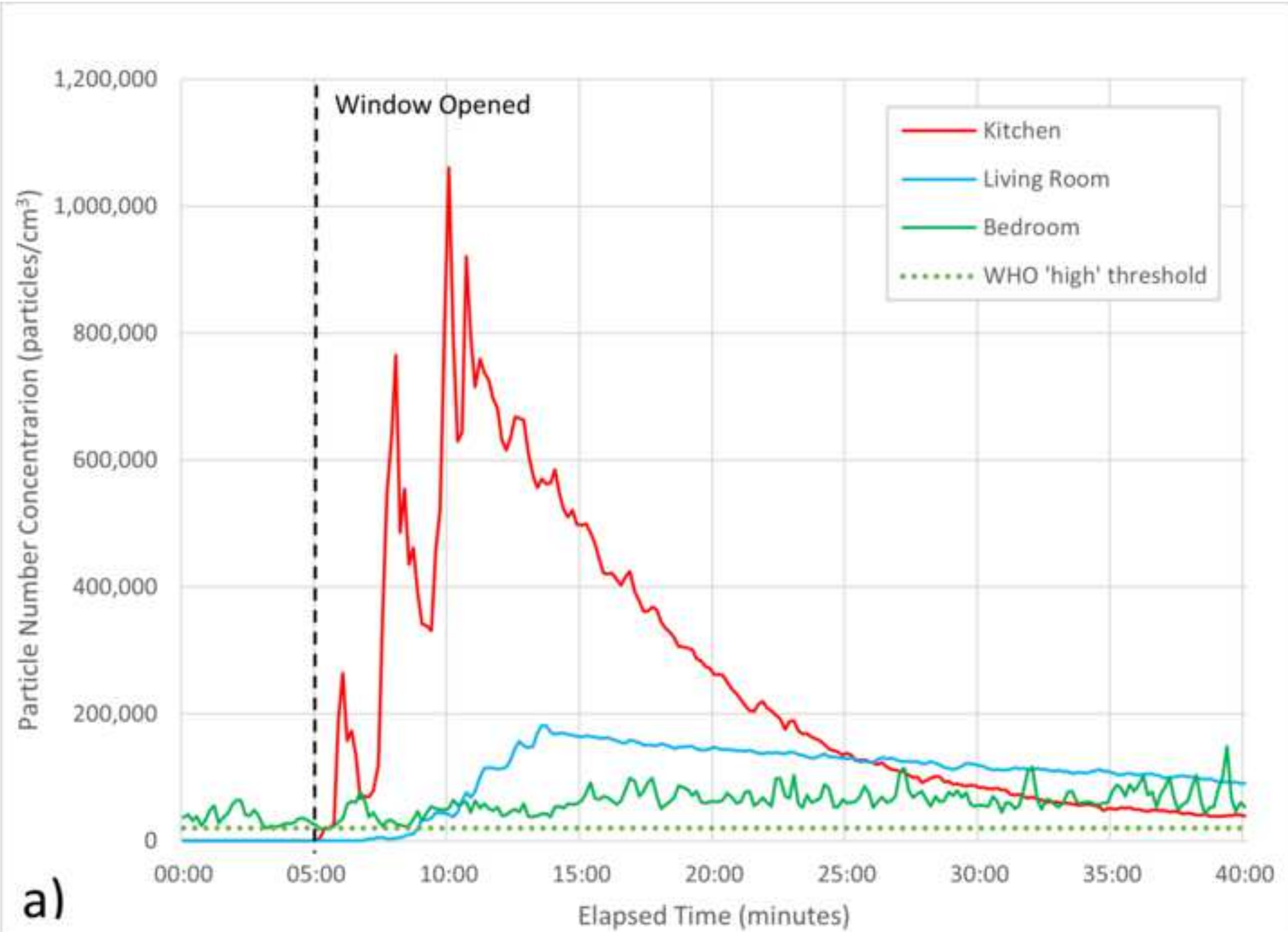

Figure 3b (revised)

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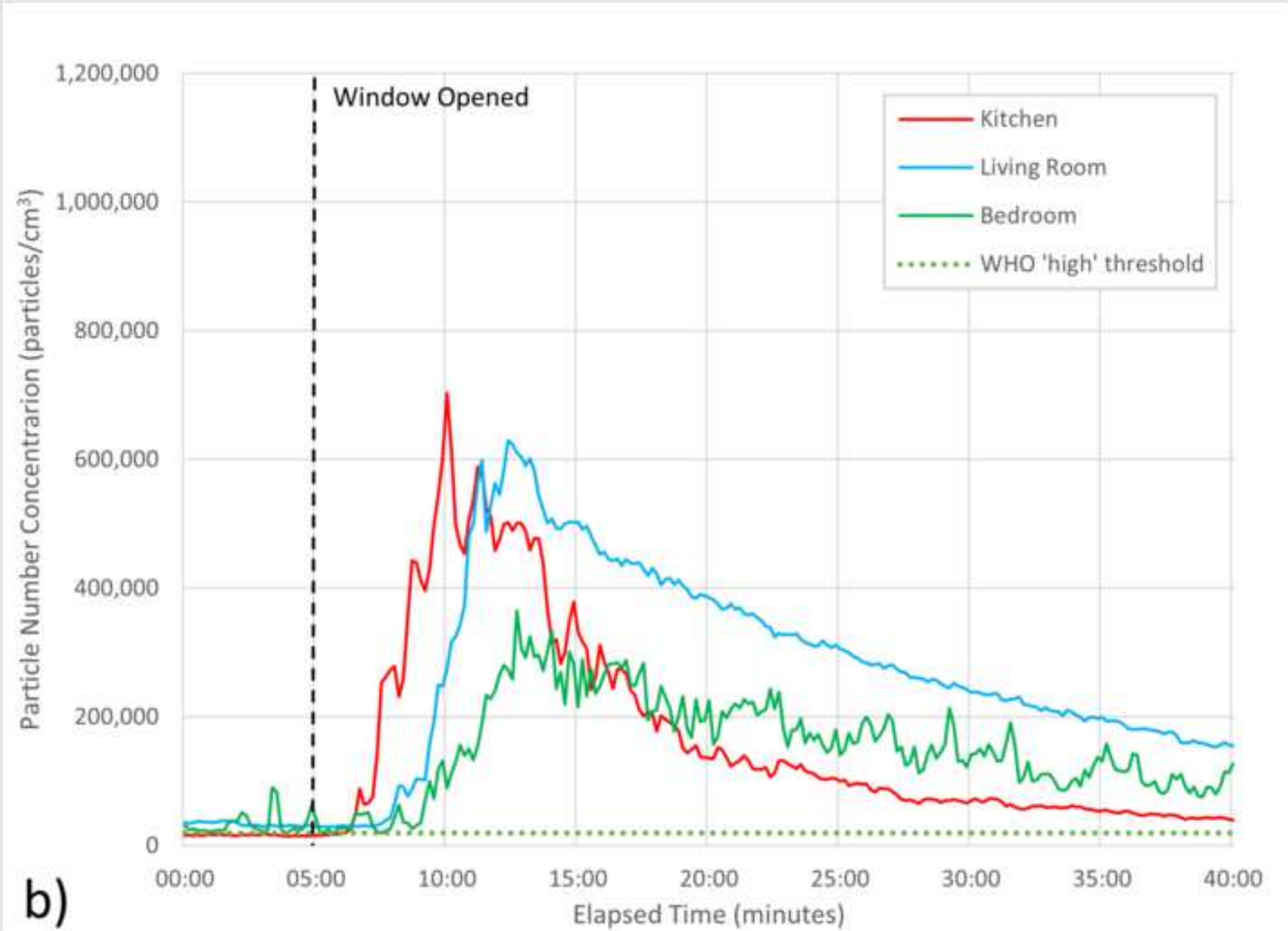
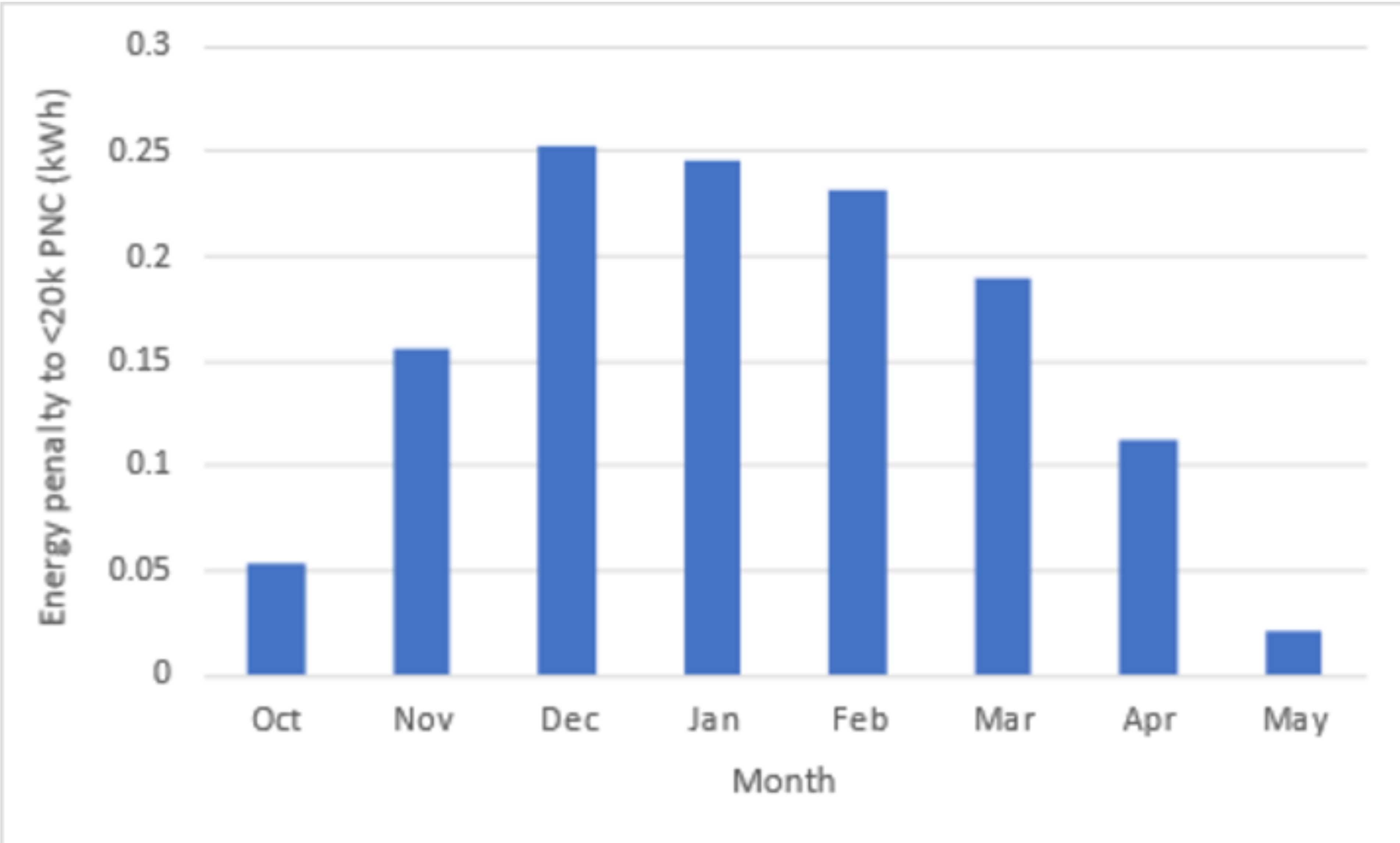


Figure 4


Energy penalty to <20k PNC (kWh)
0.3
0.25
0.2
0.15
0.1
0.05
0
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Month

Declaration of interests

☐The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☒The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

The indoor air quality research reported in this paper was conducted using air quality monitoring equipment from one of the authors company, National Air Quality Testing Services Ltd (NAQTS). However, there was no financial benefit from this paper. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary Material (1)

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