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Exposure to Indoor Air Pollution Across Socio-economic Groups: A review of the literature and a modelling methodology

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SUMMARY
Disparities in outdoor air pollution exposure between populations of different socio-economic status is a growing area of research, widely explored in environmental health literature. However, in developed countries, around 80% of time is spent indoors, meaning *indoor* air pollution may be a better proxy for personal exposure. Building characteristics and occupant behaviour mean indoor air pollution may also vary across socio-economic groups, leading to health inequalities. Following the results of a review carried out into indoor air pollution disparities, we incorporate socio-economic information into an indoor air quality model in order to evaluate exposure disparities in the indoor environment. The building physics tool *EnergyPlus* was used to model the effect of two policy interventions on indoor exposure to $PM_{2.5}$ in two socio-economically different populations. Results suggest that households of low socio-economic status may be disproportionately affected by building and/or environmental policies which are implemented without consideration of the wider socio-economic processes governing the space.

KEYWORDS
Household air pollution; socio-economic status; indoor environment modelling; building physics; energy efficiency;

1 INTRODUCTION
Building characteristics - such as build quality, volume and ventilation - and occupant behaviour, mean indoor air pollution may vary across socio-economic groups (Ferguson et al, 2020). Previous work by the authors carried out a review of indoor exposure disparities in developed countries, finding that households of low socio-economic status experience higher levels of indoor particulate matter (PM_{10}, $PM_{2.5}$), NO_2, volatile organic compounds (VOCs) and environmental tobacco smoke (ETS), whilst higher indoor radon concentrations were found in more affluent homes (Ferguson et al., 2020). Results are outlined in Table 1. This can lead to health inequalities in developed countries where around 80% of time is spent indoors. Policy-mediated changes to the built environment can lead to unintended consequences on occupant

health via the dichotomy between increased energy efficiency and indoor air quality (IAQ) (Broderick et al., 2017). Given their limited resources to adapt to changing conditions, vulnerable populations within society, such as those of low socio-economic status (SES), may be disproportionately affected by the unanticipated effects of policies which are implemented without consideration of the wider socio-economic processes governing the space. IAQ modelling is a growing area of research offering a methodology through which evidence regarding adaptions to the built environment can be robustly examined before implementation, preventing impacts falling disproportionately on those of low SES and reducing inequalities. This can be achieved by incorporating socio-economic information into IAQ modelling, but this is not yet widely explored in the literature, meaning inequalities may be overlooked.

Table 1. Review of indoor air pollution disparities.

Location	Air pollution estimate	Pollutant	Socio-economic measure	Association
South Korea, (Son et al., 2003)	Home measurements	VOCs	Household income	Low-income homes had benzene concentrations 62.47 $\mu g/m^3$ higher than the control homes.
US (Zota et al., 2005)	Home measurements	NO_2	Occupant density	Occupant density was a significant predictor of indoor NO_2 concentrations, with a univariate coefficient of 3.2.
US (Baxter et al., 2007)	Home measurements	$PM_{2.5}$	Occupant density	Increased household occupant density was associated with a 4.11 $\mu g/m^3$ increase in indoor $PM_{2.5}$
South Korea (Byun et al., 2010)	Home measurements	PM_{10}	Household expenses	PM_{10} decreased by 6.61 $\mu g/m^3$ as average monthly expenses increased.
Spain (Esplugues et al., 2010)	Home measurements	NO_2	Educational attainment	NO_2 levels were 0.07 $\mu g/m^3$ higher in homes with the lowest educational attainment.
US (Storm et al., 2010)	Home measurements	VOCs	Household income	Indoor concentrations were six times higher in homes in the lowest income category (105.5 $\mu g/m^3$ vs. 17.8 $\mu g/m^3$).
France (Brown et al., 2015)	Home measurements	$PM_{2.5}$	Employment status	$PM_{2.5}$ concentrations were 38.8 $\mu g/m^3$ for employed households and 62.1 $\mu g/m^3$ for unemployed.
US (Casey et al., 2015)	Building measurements	Radon	Deprivation index	Radon concentration were 118.4 Bq/m^3 higher in the basements of buildings in the lowest deprivation category.
UK (Kendal et al., 2016)	Home measurements	Radon	Social class	Indoor radon concentrations decreased from 29.4 Bq/m^{-3} to 18.4 B/qm^{-3} as social class of home decreased.
UK (Shrubsole et al., 2016)	Building simulation	$PM_{2.5}$	Household income	Homes below the LIT* experienced higher indoor PM concentrations.
US (Rosofsky et al, 2018)	Linked 3 public datasets	$PM_{2.5}$	Household income	Areas of with high indoor exposures were comprised of 23% households below the median income, compared with 7% in areas with the lowest indoor exposures.

*Low-income threshold.

2 MATERIALS/METHODS

The building physics model, *EnergyPlus*, was used to model the IAQ of two populations of different SES. Two policy interventions were evaluated as a proof of concept: The effect of a home energy-efficient retrofit and outdoor concentration reductions. Outdoor $PM_{2.5}$ concentrations were reduced to 10 $\mu g/m^3$ from baseline values, in line with the UK Clean Air Strategy (DEFRA, 2019), and building energy-efficiency was upgraded according to a typical home retrofit. Childhood home exposure to $PM_{2.5}$ was modelled for summer and winter weekends, in households identified by the English Housing Survey as above and below the low-income threshold (LIT). The LIT is defined as homes which live on less than 60% of the UK's median income (Francis-Devine et al., 2019). Children have increased likelihood of experiencing negative health impacts from air pollution exposure due to their immature immune and lung systems (Zhang et al., 2016). Thus, the study investigated if children from low SES households have elevated indoor exposure to $PM_{2.5}$ compared with those in the general UK population. The main air pollution parameters are outlined in Table 2.

Table 2. $PM_{2.5}$ emission, deposition rates and production schedules.

Source	Emission/ Deposition	Schedule
Cooking	1.6mg/min[a] (emission)	09:00 - 09:20 (kitchen)
	$0.19h^{-1}$[b] (deposition)	12:00 – 12:30 (kitchen)
		17:30 – 18:00 (kitchen)
Smoking	0.9mg/min[a] (emission)	12:00 – 12:05 (kitchen)
		12:30 – 12:35 (kitchen)
	$0.10h^{-1}$[c] (deposition)	17:00 – 17:05 (kitchen)
		18:00 – 18:05 (kitchen)
		10:00 – 10:05 (lounge)
		11:00 – 11:05 (lounge)
		15:00 – 15:05 (lounge)
		16:00 – 16:05 (lounge)
		19:00 – 19:05 (lounge)
		20:00 – 20:05 (lounge)
		21:00 – 21:05 (lounge)

Production schedules were for weekends only.
[a]Dimitroulopoulou, Ashmore, Hill, Byrne and Kinnersley, 2006
[b]Long et al., 2001
[c]Klepeis and Nazaroff, 2006

Socio-economic effects were introduced into the model via the outdoor concentration levels, building archetype composition and the indoor smoking prevalence. The modelling frame work is outlined in Figure 1. Data sources used are representative at the national level and freely available in the UK.

Outdoor concentration levels

For outdoor concentrations, monitored data from the London Air Quality Network (LAQN) was used, a website providing information on external air pollution levels across London and South East England. As outdoor levels of air pollution display strong socio-economic patterning (Goodman et al., 2011), concentrations were taken from Tower Hamlets, the London Borough with the highest income equality (Tinson et al., 2017) for the low socio-economic case. In houses above the LIT, monitored $PM_{2.5}$ data from Bexley, a relatively affluent borough in South East London, were used.

Building archetype composition

Exposure was modelled across eight building types broadly representative of the UK domestic building stock. As dwelling type has long been considered a reliable metric of material circumstance, archetypes were weighted according to empirical survey data in the UK, with values outlined in Table 2. The table shows that smaller dwellings, such as flats, are more commonly occupied by those of lower socio-economic status. As they often share a number of party walls, floors or ceilings with other dwellings, this may lead to exchange of air pollution with neighbouring dwellings (Fabian et al., 2016).

Indoor smoking prevalence

Smoking was assumed to occur indoors and prevalence rates are shown in Figure 1. These were determined by empirical data from the Office for National Statistics (ONS), which found that those in routine and manual occupations were more than twice as likely to smoke than those in other occupations, shown in Figure 1 (ONS, 2019). To isolate the role of the building on modifying exposure from outdoor sources, indoor sources were removed when evaluating the effect of outdoor concentration reductions, due to their dominant impact on daily exposures.

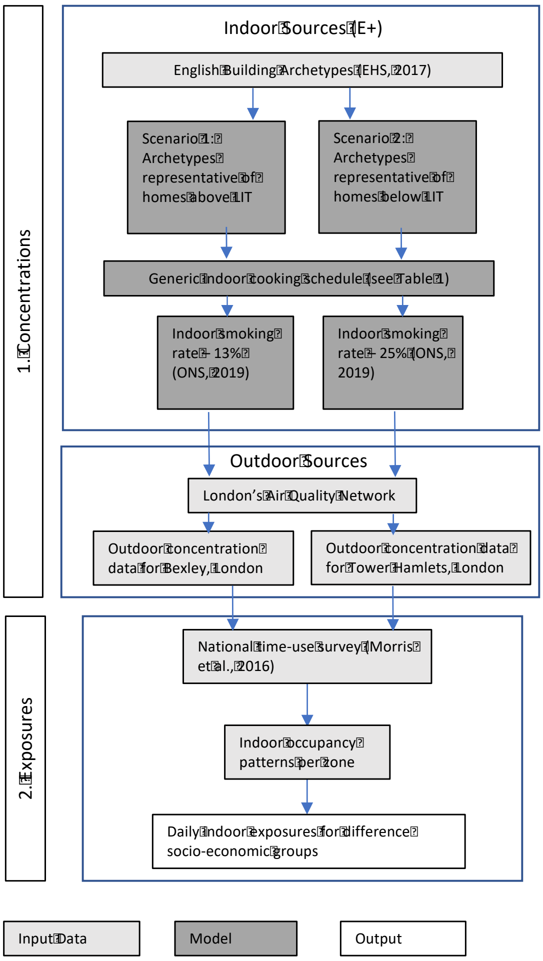

Figure 1. Flow chart outlining data inputs for the modelling framework.

Table 3. Dwelling archetypes (EHS, 2017).

Archetypes	Households above LIT (%)	Households below LIT (%)
End terrace	6.0	8.1
Mid terrace	21.2	20.5
Semi-detached	13.8	8
Detached	3.3	0.7
Bungalow	1.6	0.7
Converted flat	9.6	10.7
Purpose built flat, low-rise	35.8	40.1
Purpose built flat, high rise	8.7	11.2
Total	**100**	**100**

3 RESULTS

Energy Efficiency Retrofit Policy

Results of the home retrofit are presented in Figure 2a. As no additional ventilation features have been provided, the energy upgrade has increased exposure to $PM_{2.5}$ in the home for both cases, from smoking and cooking activities, by reducing the extent of background ventilation. This was particularly pronounced in the low SES model as indoor levels were higher as a result of higher indoor smoking rates and smaller dwellings which have a lower volume for the distribution of indoor-sourced particles. Levels were higher on winter weekends due to the lower dwelling air exchange rates caused by less frequent window-opening.

Outdoor Air Pollution Policy

Results of outdoor concentration reductions are presented in Figure 2b. In the absence of indoor sources, both homes above and below the LIT had similar levels of indoor $PM_{2.5}$ of outdoor-origin on winter weekends. This is likely due to the higher air exchange rates buildings with more external walls have: Free-standing dwellings, such as detached homes, experience outdoor infiltration from all aspects, leading to greater indoor levels despite the lower ambient concentrations, versus the higher concentrations in the lower SES case. In summer, average diurnal levels were higher in households below the LIT due to the higher baseline outdoor concentrations and the higher summer air exchange rates as a result of window opening. No change was seen in households above the LIT in summer, as outdoor levels were already below the guideline limit.

A B

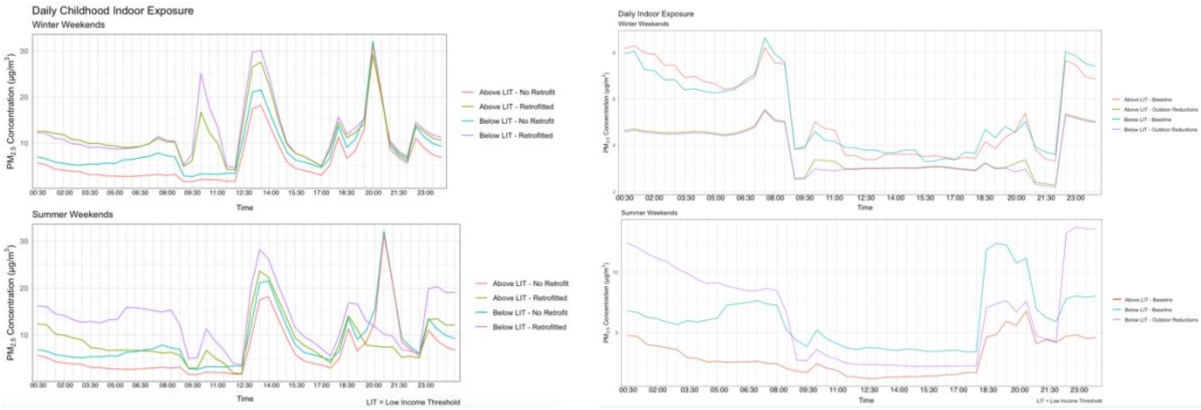

Figure 2. Childhood daily $PM_{2.5}$ exposure across retrofitted and non-retrofitted homes (a) and from infiltration of outdoor sourced $PM_{2.5}$ in the home (b) for households above and below the LIT.

4 DISCUSSION

The model provides a useful approximation of daily exposure at home: Energy-efficient modifications can negatively affect IAQ and impacts may fall disproportionately on those of low SES. Even in the absence of indoor sources, disparate indoor levels can arise between households of various SES due to the underlying dwelling archetype and building permeability. However, a single, standard cooking profile was used – different cooking techniques can lead to appreciable differences in the amount of particulate matter emitted indoors (Abdullahi et al., 2013) - which was not accounted for in this model. Despite modelling uncertainties, the tool highlights how policy interventions targeting domestic IAQ should consider the wider building and behavioural factors in a socio-economic context.

5 CONCLUSIONS

Reducing unequal exposures to indoor air pollution provides an avenue through which inequalities can be mitigated, given the socio-economic biases present in indoor exposures. The data used in this work for outdoor pollution concentrations, smoking prevalence and building types are commonly collected at the national level across much of the developed world, thus the framework proposed here may be applicable to areas beyond the study area. Access to clean outdoor air leverages considerable political support and is a contemporary talking point, whilst indoor air pollution can be overlooked. Highlighting how exposure to indoor air pollution varies across socio-economic groups at the building stock-level can bring the cause high on the political agenda and result in practical action.

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