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Inequalities in exposure to indoor environmental hazards across England and Wales – can more energy efficient homes help?

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Abstract. Housing is an important modifier of outdoor environmental hazards due to features such as the amount of passive and active ventilation a dwelling receives, the proportion of the façade that is glazed and the building's thermal insulation levels. Using Artificial Neural Networks based on an indoor building physics model, we simulate indoor temperature and air pollution concentrations in ~15 million English and Welsh dwellings and assess how exposure to indoor hazards varies for different population groups. The model is derived using simulations from the dynamic thermal modelling tool *EnergyPlus*, taking a spatially-distributed housing stock as input. Results are linked to the latest 2021 Census data on area-measures of population demographics to assess if vulnerable subgroups bear a disproportionate risk from indoor environmental hazards. We find neighbourhoods in England and Wales with a higher proportion of infants, ethnic minorities and income-deprived populations experience higher two-day maximum indoor temperatures in summertime; whilst more ethnically diverse areas have elevated annual average indoor concentrations of outdoor-sourced $PM_{2.5}$. Areas with a higher proportion of those aged 65+ had a lower standardised indoor temperature (SIT) in winter, increasing the risk of fuel poverty. We then implement a stock-wide, home energy retrofit, in line with national decarbonisation targets. Results suggest energy-efficient building interventions may exacerbate heat inequalities without the provision of external shading, but improve population exposure to winter indoor temperatures and indoor concentrations of ambient-sourced $PM_{2.5}$.

1. Introduction

The UK built environment is currently facing a number of challenges, including the per-unit increase in domestic energy prices, placing an estimated 15 million households in fuel poverty this winter, the threat of increasing summertime temperatures and ambient air pollution concentrations regularly breaching national and international guideline limits [1]. As the population spends up to 95% of their time indoors, much of our exposure to external temperatures and ambient air pollution concentrations will be modified by buildings.

Housing is an important modifier of population health [2]. Whilst there is an increasing amount of evidence highlighting the synergistic effect of outdoor air pollution exposure and high temperatures on health [3], little of this work considers the impact of buildings in mediating indoor exposure to air pollution and high summertime temperatures and the role dwelling characteristics may have. There are a number of building and environmental features which may exacerbate high temperatures and air pollution concentrations in the indoor environment that are more commonly features of vulnerable homes, such as reduced background ventilation and being located in urban areas within the urban heat island (UHI) where ambient temperatures and air pollution concentrations are higher [4,5].

Running parallel with these environmental hazards is the need for the poor-performing housing stock to meet national decarbonisation targets [6] in order to reduce space heating demand and tackle rising fuel poverty rates. Improving the energy efficiency of dwellings via home insulation measures can improve health and lower operational costs for the occupants [7], and reduce reliance on increasingly insecure fuel supplies in the UK. However, summertime overheating is becoming an issue more commonly observed in energy-efficient housing [8] along with elevated indoor concentrations of indoor air pollution [9].

An analysis of indoor temperatures and air pollution concentrations before and after a home energy retrofit is, therefore, necessary to assess if the planned decarbonisation goals are at odds with maintaining environmental health in the UK, particularly for more vulnerable groups, which may spend a greater amount of time indoors at home [4].

2. Methods

2.1. Metamodel

The model is based on Artificial Neural Network models (ANN) derived from a large number of *EnergyPlus* simulations. EnergyPlus is an extensively validated, building physics software, which dynamically models building performance, taking into account the outdoor climate and terrain; building characteristics such as geometry, fabric, airtightness, floorspace; and occupant behaviour (e.g. window opening frequency and internal gains) as inputs [10]. Window-opening was modelled according to an indoor temperature threshold where windows open throughout April - September when the zonal temperature exceeds 22°C but remain closed if the outdoor temperature exceeds the indoor temperature ($T_{out} > T_{in}$). Likewise, the heating temperature setpoint was set at 21°C across all dwellings and remained the same following the energy-efficient retrofit.

The meta-model is derived from EnergyPlus simulations for indoor temperature and air pollution concentrations. Alternative scenarios are then modelled using a geo-located housing stock dataset containing the same input parameters the meta-model was trained on for a different set of dwellings. Geo-located dwelling input data was taken from the Energy Performance Certificates (EPC) register. Data is available from 2008 onwards and dwellings enter the register whenever they are constructed, sold or let, meaning that newer, more energy efficient dwellings are overrepresented in the database. Data for English and Welsh properties is publicly-available through the EPC open data portal [11], for a total of 15.8 million English and Welsh dwellings (64% of the existing housing stock). Despite the significant data coverage, it is acknowledged the sample will be biased towards more energy-efficient housing. Dwelling energy efficiency and permeability (25 percentile = 10 $m^3/h.m^2$ @ 50pa; median = 13 $m^3/h.m^2$ @ 50pa; 75 percentile = 16 $m^3/h.m^2$ @ 50pa) is estimated from raw EPC data using the UK Governments Standard Assessment Procedure (SAP) for Energy in Buildings [12].

2.2. Outputs

Three outputs were used to assess population exposure to indoor temperature and air pollution levels. Both indoor temperature metrics were assessed against a given outdoor temperature to isolate the effect of the building.

- The standardised indoor temperature (SIT) in winter. This is calculated by regressing the indoor temperature against the outdoor temperature for each dwelling, before predicting the indoor temperature when the outdoor temperature is 5°C from the dwelling-specific regression equation.
- The average two-day maximum indoor temperature in living rooms between the hours of 8 am – 10 pm when the outdoor temperature was between 24-26°C. This outdoor threshold was chosen as previous studies have found the relative risk of mortality increases when outdoor temperatures exceed 24.8°C in England [13].
- The annual average indoor concentration of $PM_{2.5}$ from outdoor sources. The pollutant $PM_{2.5}$ was selected as this has some of the strongest evidence for public health concern [14]. Indoor concentrations from outdoor sources were estimated by simulating an annual average infiltration

factor for each dwelling, which is an estimate of the proportion (0 – 1.0) of outdoor air pollution that infiltrates the dwelling. This is then converted to an indoor concentration level by spatially linking an outdoor annual average $PM_{2.5}$ concentration and multiplying by the infiltration factor for each dwelling. Spatially mapped outdoor $PM_{2.5}$ concentrations were taken from publicly available air pollution maps provided by UKs Department of Environment, Food and Rural Affairs (DEFRA).

2.3. *Vulnerable subgroups*

We assess indoor exposure disparities for a number of different subgroups, namely, individuals who are income-deprived; those identifying as an ethnic minority; those aged 65 years old and above and infants under five years old. These subgroups have previously been identified in other environmental health studies as having an increased risk of developing adverse health impacts from environmental hazards due to their underlying health and ability to adapt their surroundings [15]. The frequency of each population across English and Welsh Lower-layer super output areas (LSOAs - small output areas designed for comparable reporting of area-level statistics) was calculated from the most recent UK 2021 Census data for age and ethnicity, and data from the UK Department for Work and Pensions for income [16], linking to LSOA-averaged measures of indoor temperature and air pollution. A population-weighted mean temperature/air pollutant concentration was then calculated for each subgroup using the following formula:

$$1)\quad \tilde{x} = \frac{\sum x_i \times w_i}{\sum w_i}$$

Where $\bar{x}$ is the population-weighted mean indoor temperature or air pollutant concentration, x represents the mean indoor temperature/concentration for each LSOA, i, and W is the frequency of each of the four population subgroups per LSOA used to weight the indoor temperature or concentration level.

2.4. *Energy retrofit scenario*

To assess how energy efficiency interventions may impact population exposure to indoor environmental hazards, we implement a stock-wide, home energy retrofit by upgrading the thermal performance of each dwellings' windows, external walls, floor and roof. U-values for each element were taken from the English Building Regulations Approved Document L [17], which sets out target efficiency values for building elements in existing dwellings (Table 1). The overall building permeability was not altered as an air permeability target is not specified for existing dwellings in the latest Building Regulations [17].

Table 1. Energy efficiency target values for existing building elements adapted from Approved Document L of the English Building Regulations [22].

Building element		Fabric U-value required by the English Building Regulations for existing dwellings (W/m^2K)	Source
External wall	Solid wall	0.30	[17]
	Cavity wall	0.55	
Glazing		1.4 (double glazing)	
Roof		0.16	
Ground floor		0.18	

3. Results

Table 2 shows summary statistics of the socio-demographic and indoor environmental variables under the baseline stock conditions, aggregated by UK Government Office Region (GOR). Notable differences are the overall younger population of London, compared with other regions (higher infant and lower 65+ populations). London also has a high proportion of low-income individuals, along with the North East of England, and ethnic minorities. Indoor summertime temperatures and $PM_{2.5}$ concentrations were the highest in London, whilst the SIT during winter was the lowest in Wales, suggesting Welsh homes may be more inefficient whilst London dwellings have higher overheating risk for a given outdoor temperature.

Table 2. Summary statistics of the indoor environmental and socio-demographic variables for English and Welsh Government Office Regions (GOR) under the baseline housing stock conditions. Med = median, IQR = inter-quartile range.

Region	**Environmental variables**						**Socio-demographic (% of total population)**			
	Indoor $PM_{2.5}$ concentration		*SIT (winter)*		*Summer 2-day mean-maximum indoor temperature*		*Infants*	*65+*	*Minority*	*Low-income*
	Med	IQR	Med	IQR	Med	IQR				
North East	4.14	0.496	19.9	0.996	27.4	0.492	2.52	11.5	6.41	10.7
North West	4.60	0.817	19.8	1.03	27.6	0.526	2.72	10.6	12.9	9.72
Yorkshire	4.88	0.834	19.6	1.02	27.5	0.543	2.73	10.7	13.7	9.12
East Midlands	5.52	0.621	19.4	1.00	27.3	0.522	2.59	11.0	13.6	8.05
West Midlands	5.34	0.895	19.7	1.09	27.6	0.646	2.79	10.6	21.2	9.44
East of England	6.16	0.365	19.5	1.24	27.3	0.622	2.69	11.2	12.7	7.16
London	6.76	0.610	19.7	1.04	28.2	0.380	3.26	7.30	45.0	10.1
South East	6.18	0.732	19.7	1.10	27.5	0.587	2.59	11.2	13.1	6.64
South West	4.60	1.35	19.8	1.12	27.6	0.603	2.37	12.5	6.67	7.08
Wales	4.41	0.702	19.3	0.976	27.5	0.592	2.54	11.9	5.90	9.08

Figure 1 shows the two-day mean-maximum indoor temperature (A), the annual average indoor concentrations of outdoor-sourced $PM_{2.5}$ (B) and the standardised indoor temperature in winter (C) across English and Welsh LSOAs in the baseline and retrofitted housing stock scenario. The figure shows that dwellings located in areas with more low-income and ethnic minority individuals experience a higher overheating risk, as well as those with a greater infant population, though differences were less pronounced for this population group compared to the control. The housing stock-wide, home energy retrofit caused internal temperatures to increase, exacerbating exposure to high internal temperatures, particularly for ethnic minority groups. Neighbourhoods with a large ethnic minority population have higher indoor concentrations of outdoor-sourced $PM_{2.5}$ in the baseline and retrofitted scenario. Indoor exposure to $PM_{2.5}$ overall decreased following the retrofit, but exposure inequalities remained for ethnic minority groups. The population-weighted SIT in winter was lower for those aged 65 and over, increasing the risk of winter fuel poverty. Following the retrofit, the SIT increased, though those aged 65 and above still had a lower population-weighted mean indoor temperature than other population groups.

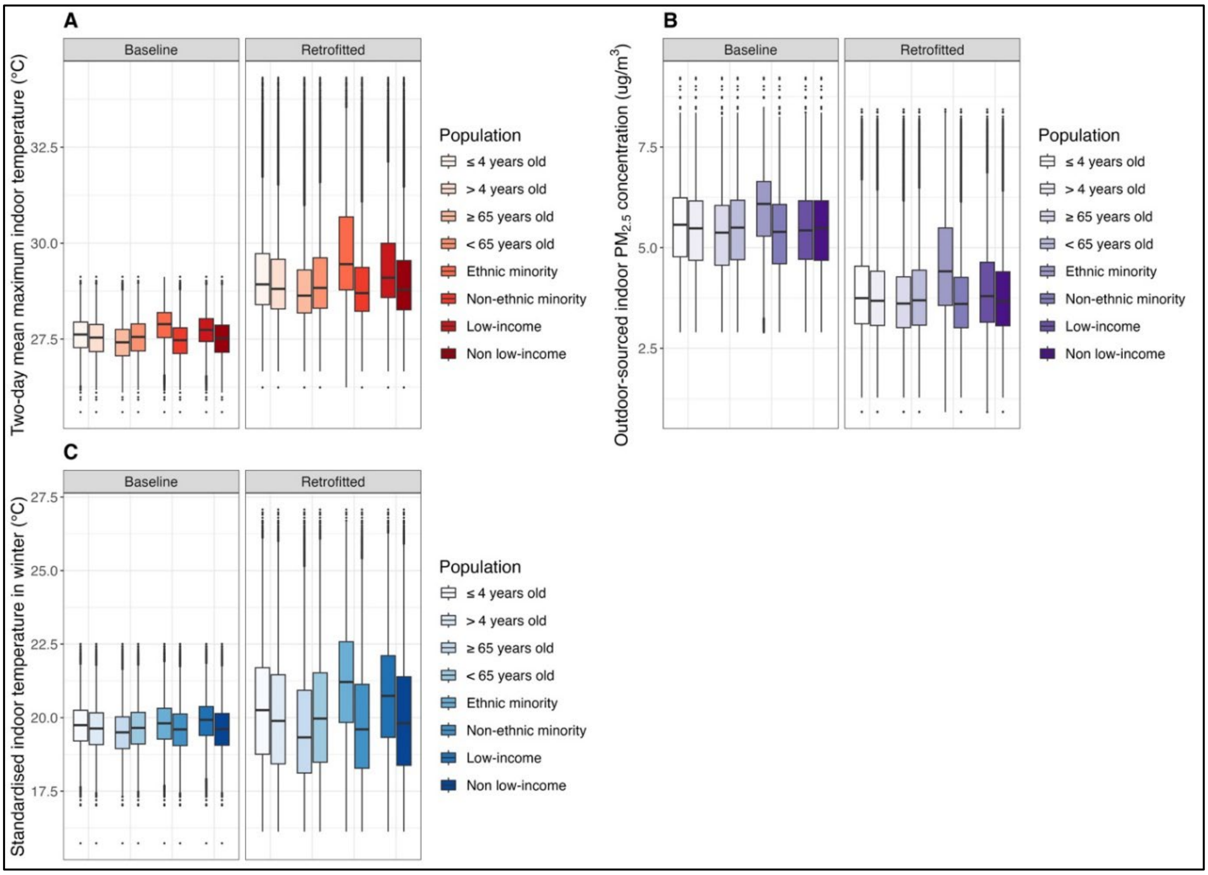

Figure 1. The population-weighted two-day mean-maximum indoor temperature when the outdoor temperature is between 24°C and 26°C in summer (A), annual average indoor concentrations of outdoor-sourced $PM_{2.5}$ (B) and standardised indoor temperature (SIT) during winter (C) for English and Welsh LSOAs under baseline (left) and retrofitted (right) housing stock conditions. Metamodel inputs are taken from the EPC register [11] for the baseline housing stock conditions and updated using energy-efficiency targets from the English Building regulations [17] in the retrofit scenario. Estimates are linked to the latest census data on age and ethnicity, and area-income estimates from the Department of Work and Pensions [16].

4. Discussion and conclusions

This work finds that homes located in neighbourhoods with a high proportion of ethnic minority and low-income individuals have higher summertime internal temperatures. Areas with larger populations of ethnic minorities additionally experienced higher concentrations of indoor $PM_{2.5}$, which is concerning given the synergistic effect of high temperatures and air pollution exposure on health [3]. Homes in areas with a larger 65+ population were generally colder in winter, potentially adding to the excess mortality burden seen amongst this age group given their underlying health vulnerability. Energy-efficient housing modifications may improve population exposure to indoor temperatures in winter and outdoor-sourced air pollution, and should be priority-targeted at more vulnerable households to improve disparate exposures. The role of energy-efficiency modifications on summertime overheating should be carefully considered in order to avoid exacerbating existing indoor heat-exposure inequalities. Including shading provision in the Building Regulations when upgrading existing dwellings may be a possible intervention to prevent this.

Lomas et al. [18] found lower-income homes are more likely to suffer from high internal temperatures during summer, supporting our findings. We additionally find that Wales has the lowest mean SIT during winter. This supports findings that the Welsh housing stock is the oldest and poorest performing of the UK housing stock [19] and highlights a key area for the spatial prioritisation of energy retrofit policy.

There is a lack of UK data on exposure to indoor environmental hazards and its relationship with occupant ethnicity or race, though minority groups are more likely to live in areas with higher *outdoor* air pollution concentrations in England [20]. Racial disparities in exposure to environmental heat have been identified in the US [21], but this is the first study to the authors' knowledge that demonstrates households in areas with a high proportion of ethnic minorities in England and Wales may experience elevated exposure to summertime indoor temperature and air pollution concentrations.

Summertime indoor temperatures increased following the energy-efficient upgrade of the building fabric elements, without the provision of external shading, supported by [8]. Indoor concentrations of $PM_{2.5}$ from outdoor sources decreased following the home retrofit, supported by [9], highlighting a potential co-benefit of UK home decarbonisation policies, though purpose-provided ventilation may be necessary to ensure $PM_{2.5}$ from indoor sources does not increase.

With rising inequality in England and Wales, housing and environmental conditions play an important role in generating health inequalities from social disadvantage. Building physics based modelling techniques provide an effective tool to support policy aiming to improve environmental conditions, meet national decarbonisation goals and reduce health inequalities.

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