Impacts of energy efficiency retrofitting measures on indoor PM2.5 concentrations across different income groups in England: a modelling study

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Abstract

As part of an effort to reduce carbon emissions in the UK, policies encouraging the energy-efficient retrofit of domestic properties are being implemented. Typical retrofits, including installation of insulation and double glazing can cause tightening of the building envelope which may change indoor air quality (IAQ) impacting occupant health. Using the example of $PM_{2.5}$ (an airborne pollutant with known health impacts), we consider the influence of energy-efficient retrofits on indoor $PM_{2.5}$ concentrations in domestic properties both above and below the low income threshold (LIT) for a range of tenancies across England. Simulations using EnergyPlus and its integrated Generic Contaminant model are employed to predict indoor $PM_{2.5}$ exposures from both indoor and outdoor sources in building archetypes representative of (1) the existing housing stock and (2) a retrofitted English housing stock. The exposures of occupants for buildings occupied by groups above and below the LIT are then estimated under current conditions and following retrofits. One-way ANOVA tests were applied to clarify results and investigate differences between the various income and tenure groups. Results indicate that all tenures below the LIT experience greater indoor $PM_{2.5}$ concentrations than those above suggesting possible social inequalities driven by housing leading to consequences for health.

Keywords: Unintended consequences, low-income housing, low income threshold, $PM_{2.5}$, retrofit.

1. Introduction

The UK Government, motivated by Greenhouse Gas (GHG) emission reduction targets, has begun to implement policies designed to improve the energy efficiency of both new and existing domestic buildings (HM Government, 2010). With existing dwellings predicted to represent 70-80% of the 2050s building stock (Boardman, 2008; Palmer & Cooper, 2011), much of the energy efficiency gains must be obtained through the retrofit of current properties. Using a number of policy mechanisms, the UK government intends these existing dwellings to undergo extensive retrofitting with a range of measures that will increase air tightness, insulation, provide glazing improvements and improve the efficiency of heating systems in order to help meet the UK's ambitious GHG reduction targets (80% reduction of 1990 emissions by 2050) (DECC, 2012). The likelihood of a wide ranging series of unintended consequences, caused by policy framing and implementation that is narrowly focused on climate change mitigation has been previously noted (Davies & Oreszczyn, 2012). These unintended consequences may impact building fabric, human health and wellbeing, the local and wider society and the environment (Shrubsole et al., 2014).

One prominent consequence with implications for population health is the change to Indoor Air Quality (IAQ) and personal exposure to airborne pollutants such as particulate matter (PM); the smaller fractions (aerodynamic diameter of 2.5 microns or less - $PM_{2.5}$) of which are particularly harmful to health (COMEAP, 2009). $PM_{2.5}$ is a significant health issue in the UK, with the 2011 fraction of mortality attributable to particulate air pollution estimated to be 5.4% nationwide (based on outdoor $PM_{2.5}$ exposure), representing in excess of 24,000 deaths in 2011 (ONS, 2012; PHE, 2013).

With the UK population spending around 80% of their time indoors, and around half

(48 to 53%) of their time in their own homes (Kornartit et al., 2010), the built environment and occupant behaviour have the potential to act as significant modifiers on population exposure to pollution from both outdoor and indoor sources (Crump et al., 2011; Sharpe and Shearer, 2012). $PM_{2.5}$ from external sources, such as emissions from traffic and industry, may infiltrate dwellings; with building location, height, number of exposed façades, orientation to outdoor pollutant sources and meteorology all impacting the amount of $PM_{2.5}$ entering naturally ventilated dwellings (Godish and Spengler, 2004; Patra et al., 2008). In mechanically ventilated dwellings where systems are correctly installed and maintained, they can influence air change rates and filter pollutants, thereby reducing $PM_{2.5}$ concentrations from both indoor and outdoor sources (Shrubsole et al, 2012).

Indoor sources of $PM_{2.5}$ may include particulates from regular activities such as the burning of fuels, cooking, smoking and cleaning (Long et al., 2001; Klepeis & Nazaroff, 2006), as well as less frequent but high-emission activities such as construction and refurbishment work (Milner et al., 2005; Weschler, 2009). In multi-dwelling buildings such as apartment complexes, inter-dwelling transfer of pollutants via party wall permeability may also occur (Molnár et al., 2007; Jones et al., 2013a). Once present inside a dwelling, $PM_{2.5}$ is removed through deposition and exfiltration, and extraction by any mechanical systems. There is also the potential for re-suspension of deposited particulates due to occupant movement and domestic activities (Gehin et al., 2008).

Previous studies have indicated that indoor $PM_{2.5}$ concentrations can be higher relative to external levels due to internal sources (Chen and Zhao, 2011), and that increases in indoor $PM_{2.5}$ levels can occur following energy efficient refurbishment without additional purposed-provided ventilation (Gens et al., 2014). Interventions that lead to increased airtightness without compensatory purpose-provided ventilation have been shown to increase exposure to indoor sourced $PM_{2.5}$ (Wilkinson et al., 2009; Shrubsole et al., 2012).

The type and quality of dwellings inhabited and the practices of the occupants may vary according to socio-economic status and income level, which may then influence pollution exposure. The UK Government, the European Union and many other countries define low-income households as those having a household income less than 60% of the national median income that year (DCLG, 2013). Occupants in houses below the lower income threshold (LIT) are more likely to live in smaller dwellings such as flats, which may have lower air change rates then detached, semi-detached, or terraced dwellings due to the reduced number of external facades (Taylor et al, 2014a). Below LIT households may also differ from the overall building stock in terms of building retrofit levels. In addressing the socioeconomic and behavioural issues that influence the adoption of energy efficiency measures, Tovar (2012) concludes that households including single adults, those living alone or in cities, lone parents, and tenants in the private sector are the least likely to adopt cavity insulation, loft insulation, and boiler upgrades. Hamilton et al (2014) however showed that dwellings with the highest take-up of fabric interventions e.g. cavity wall insulation, loft insulation and glazing (the top 20%) are more likely to be found in areas with low income, in part attributable to council-led retrofits in public housing, and schemes such as Warm Front and the Energy Company Obligation (ECO) (Warm Front, 2004; ECO, 2014). These findings indicate a potential difference in pollutant exposure between different income and tenure groups and require investigation to clarify the possible impacts on health and to better inform housing policies aiming to target and improve energy efficiency of the housing stock

(HM Government, 2010).

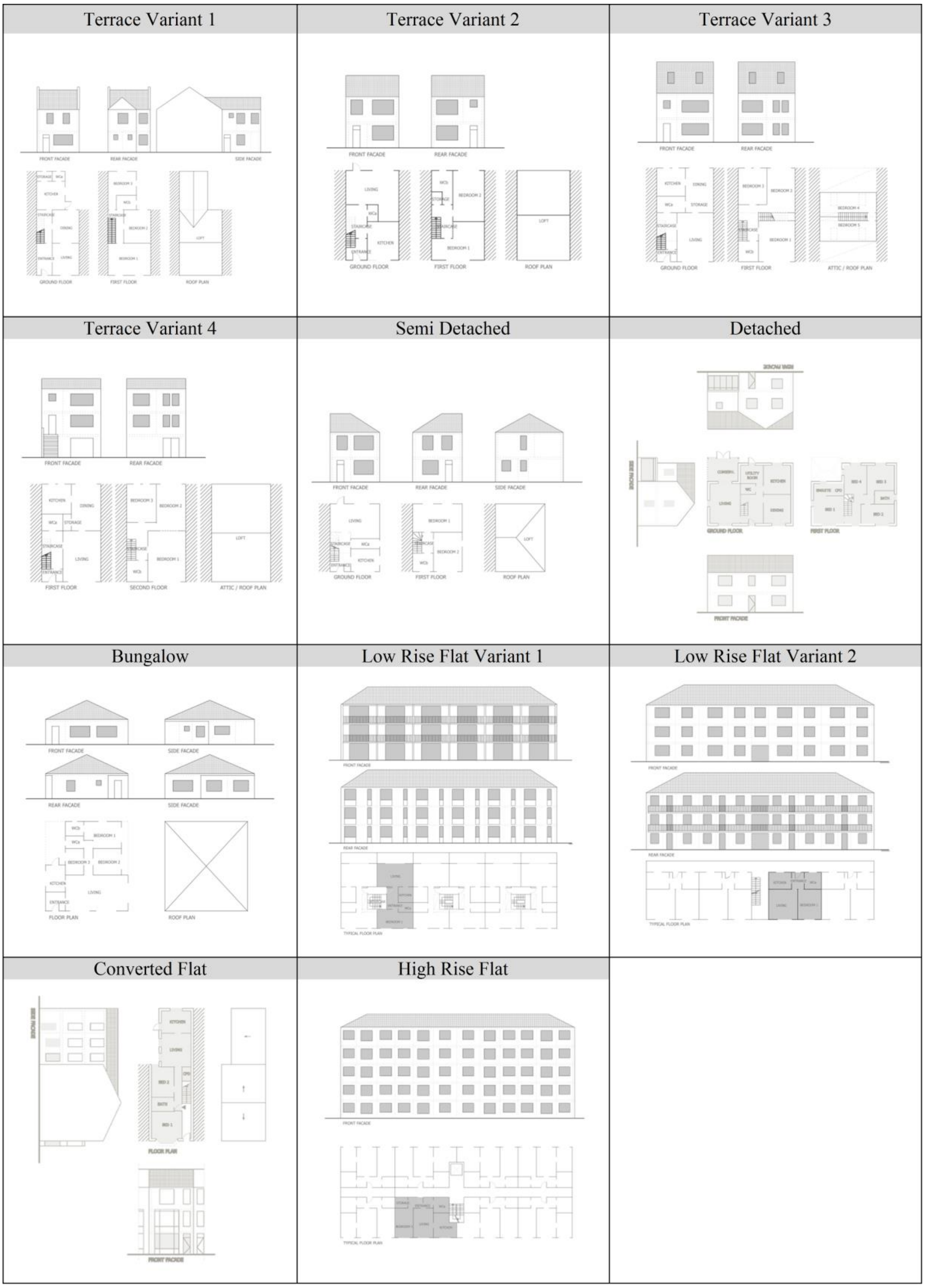
Occupancy and behavioural differences across income groups may also lead to differing levels of exposure to indoor air pollution. In the UK there is a strong link between smoking and income class, with 35% of unemployed adults smoking (compared to a rate of 19% in the economically active population). While smoking may not necessarily always occur inside the home, 59% of daily smokers surveyed allowed smoking in their homes (ONS, 2007). This is likely to be elevated amongst those with mobility issues who are less able to leave their houses. In addition, extractor fans in poor housing are more likely to remain unrepaired if broken or to underperform thereby reducing ventilation.

This paper examines how the existing English housing stock may modify the exposure to $PM_{2.5}$ from indoor and outdoor sources for those in below LIT housing (and the various tenure groups within) and those in above LIT, for both current and full levels of retrofit. Using EnergyPlus, an energy analysis and thermal load simulation program with a multizone airflow and contaminant transport analysis component (US-DOE, 2013), simulations were run for the infiltration of outdoor $PM_{2.5}$ into the indoor environment and indoor sourced $PM_{2.5}$. Simulations included a set of models representing the range of ages and built forms in the current English housing stock and possible fully retrofitted stocks under the different tenancies. The results for each model were weighted according to the frequency of occurrence for each age and built form combination in the different groups studied in order to calculate the differences in total $PM_{2.5}$ exposure between them. Finally, a series of statistical tests were carried out in to further clarify the results and test for differences between the different income and tenure groups.

2. Methods

2.1. Development of representative archetypes

The 2010-11 English Housing Survey (EHS) is a statistically representative survey, comprising ~16,000 EHS dwelling variants (EHS, 2012). Each variant is associated with a weight depending on its incidence in the English housing stock, in addition to a wide range of data describing dwelling characteristics and their inhabitants. A set of 11 archetypes (Figure 1) were constructed with multiple variants representing the range of built forms in the EHS, using archetypes of dwellings from Oikonomou et al (2012) and the AWESOME project (2013) and assumed to broadly represent the English domestic stock. Where there were built forms with multiple archetypes (e.g. terraced dwellings), the simulation results were averaged across the variants to determine a single value for the built form. The resultant eight built form bins are then matched to each EHS entry.



Terrace Variant 1

Terrace Variant 2

Terrace Variant 3

Terrace Variant 4

Semi Detached

Detached

Bungalow

Low Rise Flat Variant 1

Low Rise Flat Variant 2

Converted Flat

High Rise Flat

Figure 1. Representative archetypes used to investigate the EHS data base

2.2. Dwelling permeability, retrofit level, and operation

In addition to the built form, permeability (including current and potential retrofit level), occupancy type, and indoor pollution regime were inferred for each entry in the EHS using relevant variables. These variables include: current levels of various retrofit measures, income level after housing costs (AHC) with respect to the threshold defined in the Introduction, tenure, number of smokers, and the presence of working extract fans. The four potential retrofits examined included wall and loft insulation, floor sealing, and double-glazed windows (used as a proxy for draught-proofing). These retrofits were selected as they are thought to be some of the largest contributors to infiltration according to the Warm Front study (Hong et al, 2004).

Using the EHS data, Figure 2 shows the current levels of retrofit across the various tenure categories within the below LIT group, and for the above LIT income group. Below LIT private-rented dwellings tend to have the lowest levels of retrofit reflecting the lack of decision making autonomy for either accepting or seeking energy efficiency improvements. The owner-occupied below LIT and above LIT-income categories have the second lowest levels of retrofit. The below LIT local-authority and registered social landlord (RSL) housing tend to have the highest levels of retrofit (Hamilton et al., 2014). Using the smoking data to determine the presence of at least one smoker in each EHS variant, 44% of below LIT dwellings were found to have at least one occupant that smoked, with similar levels across tenure groups. 28% of above LIT dwellings were found to have at least one occupant that smoked. Analysing the data to determine the presence of working extract fans in the EHS variants found a slight difference in levels of working kitchen extract fans across the income and tenure groups with below LIT income households 44.5% of the time, above LIT income households 48.4% of the time.

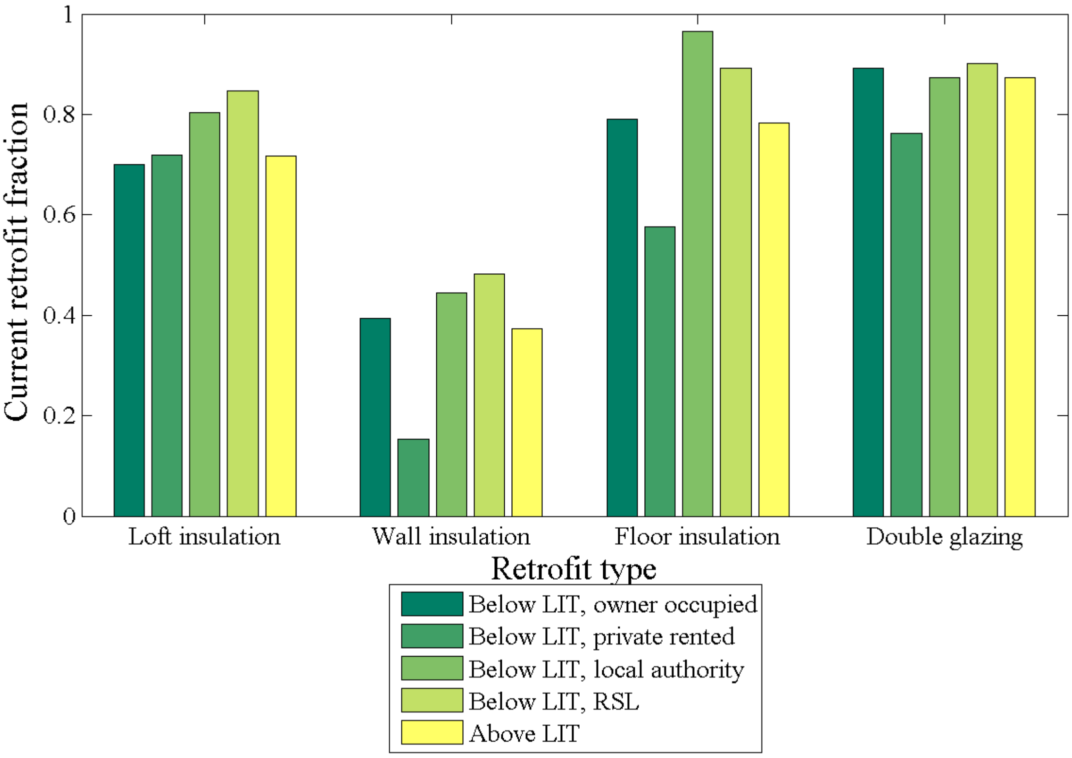


Figure 2: Current levels of various retrofit measures across income and tenure groups.

The permeability of individual dwellings in the EHS was estimated using the UK Standard Assessment Procedure (SAP) methodology (BRE, 2009) as per Taylor et al (2014a), with the exception that draught proofing and floor sealing were excluded from the calculation, as their influence on permeability was to be considered separately. Estimated changes to dwelling permeabilities caused by wall, loft, floor, and window retrofits were calculated based on estimates from the Warm Front study (Warm Front, 2004) (Table1). The current levels of retrofit were estimated for each dwelling in the EHS, based on the presence of variables reflecting wall, window, and loft improvements, while all pre-1919 dwelling were assumed to have suspended floors and be therefore eligible for floor retrofits (i.e. the sealing or concreting of a suspended floor). The presence of retrofits was used to adjust the SAP-calculated permeability accordingly. Additionally, an estimate of the final permeability following implementation of all four types of retrofit was calculated, providing an estimate of the permeability following a complete building retrofit. It was assumed that retrofits were carried out without any additional compensatory ventilation (a worst-case scenario), and that building permeability did not drop below 3m^3/hr/m^2.

Table 1. Percentage change in permeability following retrofits.

Retrofit measure	Change in permeability (%)
Pre-retrofit (PR)	0
Wall Insulation (WR)	-9
Loft Insulation (LR)	-14
Floor Sealing (FR)	-17
Double-Glazing/Draught Proofing (DGR)	-5

2.3. *Dynamic Building Simulation*

Simulations were constructed and run in EnergyPlus 8.0 using the methodology employed by Taylor et al (2014a). Although a short description is provided here, readers are advised to consult this paper for full details. Simulations were run for an entire year with both outdoor and indoor sources of $PM_{2.5}$ (smoking, cooking, and cooking without ventilation). The EnergyPlus (EP) variants comprised each of the built forms modelled at eight different permeability levels (3, 5, 7, 10, 15, 20, 25, and 30 m^3/hr/m^2@50Pa), with the more airtight dwellings (3, 5, and 7m^3/hr/m^2@50Pa) modelled with fabric characteristics with greater thermal insulation levels. This covered the full range of characteristics of the current and possible fully retrofitted housing stocks under different levels of retrofit. Each EP variant was also modelled assuming four different orientations (North, East, South, and West), to enable orientation-averaged outputs to evaluated, and both with and without trickle vents. Weather conditions were modelled using a Typical Reference Year (TRY) weather file for Central London (Islington) obtained from the Prometheus project (Eames et al., 2011) and considered sufficiently indicative of general urban conditions in England for the purposes of this study.

2.3.1. Occupant behaviour

A single occupancy scenario representative of a family was modelled. The family was assumed to be absent from the dwelling during weekdays between 9am to 5pm, and home all day during the weekends. Dwellings were assumed to be heated to 20°C during the night throughout the year, while internal gains from electrical equipment and occupant metabolism were also included in the model as seen in Taylor et al. (2014b)

Dwelling window-opening behaviour was coupled to indoor temperatures, as carried out in Taylor et al. (2014a). Living room windows were considered to be opened during the day if the internal temperatures exceeded 25°C, while bedroom windows were considered to be opened during the night if temperatures exceeded 23°C. In both cases, windows remained closed if the indoor temperatures were less than those outdoors. While there are a number of factors which may influence occupant window-opening behaviour, internal temperature is one of the most significant, and the thresholds used in this study are in line with those observed in field studies (Dubrul, 1998;Fabi et al., 2012) and CIBSE overheating guidelines (CIBSE, 2006).

2.3.2. Pollutants

$PM_{2.5}$ levels and emission schedules were modelled as per Shrubsole et al (2012); the schedule of activities can be seen in Table 2 while the $PM_{2.5}$ emission rates, outdoor particle penetration factor, and deposition rates can be seen in Table 3.

A different deposition rate was considered for Environmental Tobacco Smoke (ETS) due to the different size fraction of $PM_{2.5}$ that characterises the majority of ETS. Two ventilation scenarios were modelled during cooking with the extractor fans either on or off, while no additional ventilation was used when smoking occurred indoors. Although it is likely that the different constituents of PM$_{2.5}$ pose different risks to health, given the lack of evidence in this area, we have assumed that from PM$_{2.5}$ indoor sources are equally as toxic as those found in outdoor air.

Table 2. Indoor PM$_{2.5}$ production schedules.

Activity	Location	Schedule
Cooking	Kitchen	07:45 – 08:00 12:00 –12:30* 19:00 - 19:30
Smoking	Kitchen	8:00 – 8:05 9:00 – 9:05
	Living Room	10:00 – 10:05* 11:00 – 11:05* 12:00 – 12:05* 19:00 – 19:05 20:00 – 20:05 21:00 – 21:05 22:00 – 22:05

*represents those events that only occur on weekends.

Table 3. PM$_{2.5}$ emission rates, outdoor particle penetration factor, and deposition rates

Source	Penetration Factor	Annual Outdoor Level	Emission Rate	Deposition Rate
Outdoor	0.8 when windows closed[1] 1.0 when windows opened[1]	13μg/m^{2}[3]	_	0.19h^{-1}[3]
Cooking	_	_	1.6mg/min [4]	0.19h-1[5]
Smoking	_	_	0.9mg/min [4]	0.10h-1[6]

[1, 3 & 5]Long et al., 2001; [2]Shrubsole et al., 2012; [4]Dimitroulopoulou et al., 2006;
[6] Klepeis & Nazaroff, 2006

2.4. *Data output and analysis*

2.4.1. Data collation and matching

The hourly pollutant concentrations in the living room, bedroom, and kitchen were output from the simulations as representing those rooms most frequently occupied. The EP output files were collated and analysed using the SAS statistical package (SAS, 2013), and used to calculate the pollutant concentrations occupants were exposed to, based on the room occupied at the corresponding schedule time. The annual average concentration of $PM_{2.5}$ from outdoor sources (in absolute levels relative to the constant outdoor background of 13µg/m^3), and from cooking, cooking without extract fans, and smoking (in absolute concentration, µg/m^3) were averaged across the four building orientations for each simulated EP built form/permeability variant.

Indoor pollution levels from different sources were then assigned to each entry in the EHS based on the built form and estimated current and complete-retrofit permeability by interpolating between the different modelled permeability levels. Dwellings with post-2002 double-glazed windows were assumed to have trickle vents installed, while those installed before were considered to be without trickle vents. The presence of a working extractor fan in the kitchen in each EHS entry was used to indicate whether indoor pollution levels from cooking were with or without such a ventilation system. Smoking was similarly weighted: if a smoker was not present in the EHS variant, the $PM_{2.5}$ concentration from smoking was assumed to be zero. Estimates of the current variation and likely changes in $PM_{2.5}$ exposures following a full retrofit of the housing stock across tenure and income categories were then examined.

3. Results

The mean indoor $PM_{2.5}$ concentrations for the current housing stock and a fully retrofitted housing stock derived from the EP simulations are shown in Figure 3. These include both $PM_{2.5}$ from outdoor sources and indoor sources including smoking and cooking across various income and tenure groups.

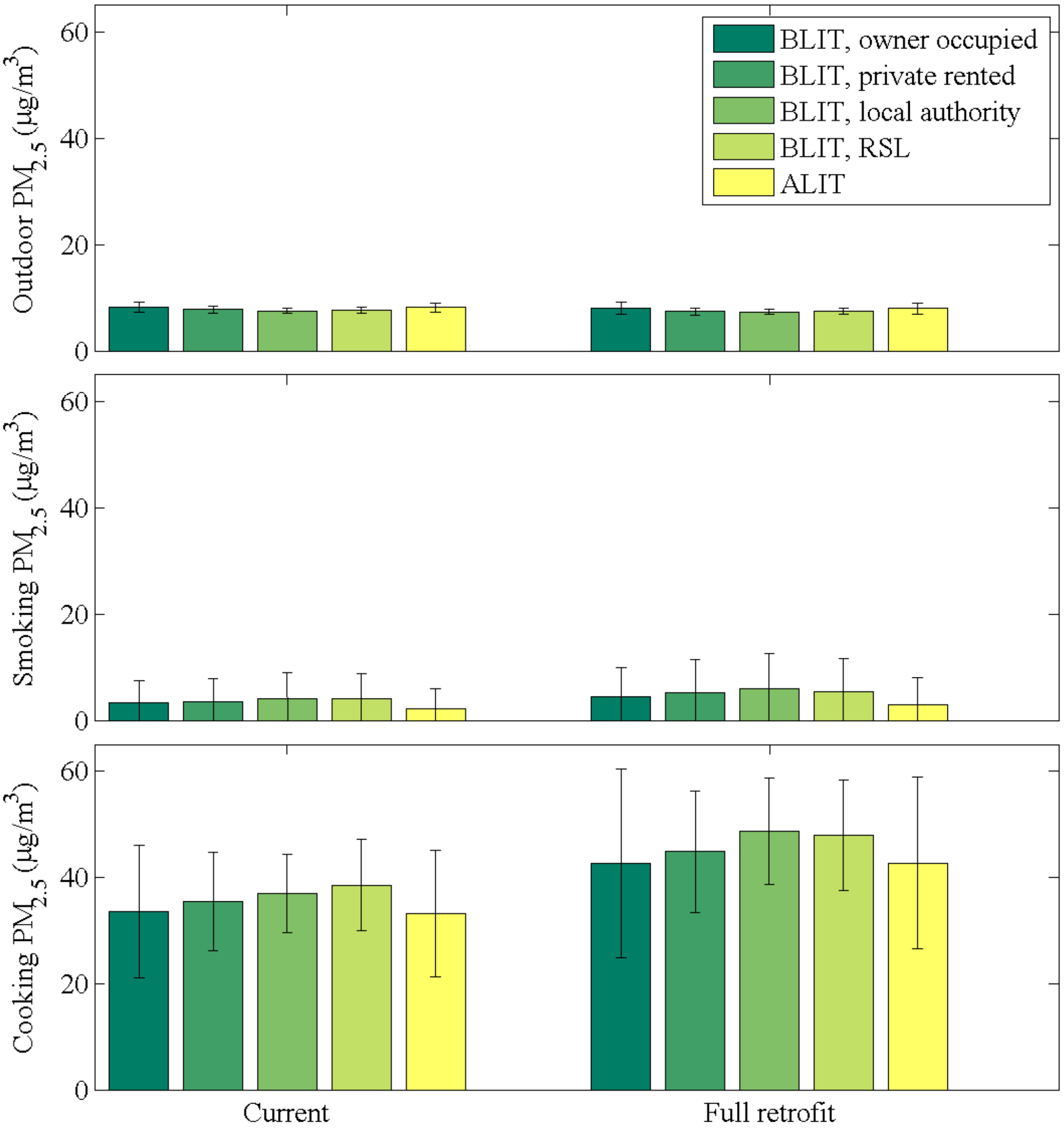


Figure 3: Indoor $PM_{2.5}$ concentrations indoors from different sources for current and fully retrofitted scenarios, and across income and tenure groups. The error bars show standard deviations, and are large for smoking due to some dwellings having zero concentrations. The cooking $PM_{2.5}$ is the exposure experienced by cooks in the kitchen of the properties

The simulations show that cooking is clearly the biggest contributor of $PM_{2.5}$ to the indoor environment and that cooks therefore receive greater exposures than occupants not present in the kitchen. From this it can be inferred that those who undertake the majority of the household cooking may experience greater levels of exposure compared to non-cooks, whilst they are both exposed to similar levels of externally generated $PM_{2.5}$. There is also a suggestion that below LIT-income groups are at higher risk of exposure to greater concentrations of $PM_{2.5}$ when compared to above LIT-income groups due to smaller houses and a smaller number of exposed facades leading to a reduced air change rate. In addition, they may experience higher rates of smoking and greater likelihood of cooking without working extractor fans. It appears that the fully retrofitted housing stock poses a higher health risk compared to the current housing stock primarily due to a general reduction in building permeability and consequent air change rate following retrofitting interventions on the building envelope. Whilst this has the effect of reducing the ingress of outdoor sourced $PM_{2.5}$ it results in an increase in concentrations of indoor sourced $PM_{2.5.}$

A series of one-way ANOVA tests were carried out in MATLAB (MathWorks, 2012) to further clarify the results and test for differences between the income and tenure groups within each of the current and fully retrofitted housing stocks, and between the current and fully retrofitted housing stocks as a whole. As there are more than two groups when comparing between income and tenure groups, MATLAB's multiple-comparison tests were subsequently carried out if the initial ANOVA test found a significant difference. These isolated the location of the differences whilst ensuring Type-II errors were adequately accounted for. The results are shown in Table 4.

Table 4: Results of ANOVA tests for the difference $PM_{2.5}$ sources. 'Yes' signifies a difference at the 95% level of confidence. The 'details' column summarises the differences as derived from the multiple-comparison tests.

Pollutant	Between current income/ tenure groups	Between retrofitted income/ tenure groups	Between current/ retrofitted groups	Details
Outdoor $PM_{2.5}$	Yes	Yes	Yes	Below LIT-income, owner-occupied and above LIT-income groups are similar to each other but different from other groups in current housing stock, though the groups are more similar in the fully retrofitted housing stock.
Smoking $PM_{2.5}$	Yes	Yes	Yes	Above LIT-income group is different from all other groups in both current and fully retrofitted housing stocks.
Cooking $PM_{2.5}$	Yes	Yes	Yes	Below LIT-income, owner-occupied and above LIT-income groups are similar to each other, but all the other groups are

				significantly different from these and from each other in the current housing stock. Similar for fully retrofitted housing stock but below LIT-income local-authority and RSL groups more similar to each other.

The ANOVA tests support significant differences in all cases at the 95% level of confidence, although it is acknowledged that this reflects differences between the modelled $PM_{2.5}$ exposures rather than actual exposures. Actual exposures may exhibit different distributions as a result of uncertainties in model variables such as the behaviour of occupants, which may also vary across income and tenure groups; dwelling characteristics that are not informed by the described data sources and variations in weather variables across dwelling locations. In the case of comparing modelled exposures between current and fully retrofitted housing stocks, the ANOVA tests highlight significant differences in the concentrations of different sources of $PM_{2.5}$ indoors: outdoor $PM_{2.5}$ decreases, smoking $PM_{2.5}$ increases, and cooking $PM_{2.5}$ increases.

4. Discussion

This study provides new insights into the average relative differences in indoor $PM_{2.5}$ exposure that exist between the various income and tenure groups of the English domestic stock. These differences in exposure are primarily driven by differences in the dwelling characteristics they occupy, but also their habits, such as smoking. In addition, the study describes the potential impacts of changes to occupant $PM_{2.5}$ exposure following an energy efficiency retrofitting scenario. Results generated from the computer modelling were analysed further to determine the statistical limits of the relative differences. Exposure levels modelled are generally consistent with previous research using different modelling programmes and techniques (e.g. Milner et al., 2005; Shrubsole et al., 2012; Gens et al., 2014), which shows that the application of energy efficiency interventions on the domestic stock, whilst reducing exposure to outdoor sourced $PM_{2.5}$ may increase exposure to indoor sources.

It is acknowledged that the choice of occupant schedules and related activities impact the indoor $PM_{2.5}$ exposure. Future work could develop a full range of schedules for different household types and explore occupant behaviour in greater detail.

It would appear that below LIT income groups have, on average, higher levels of exposure to $PM_{2.5}$ across the building stock when compared to above LIT income groups. This may in part be due to the greater uptake of measures that reduce the permeability of the building envelop and therefore lower air change rates where additional purpose provided ventilation is not provided or maintained. However, it is acknowledged that within each income band there will be a range of individual personal indoor $PM_{2.5}$ exposures. Furthermore, as with all modelling studies, a number of assumptions are required, and further empirical investigation is necessary to confirm or refute the findings. The primary $PM_{2.5}$ source appears to be from cooking, and therefore the provision, use, and appropriate maintenance of adequate extraction equipment (e.g. cooker hoods) is essential to remove this pollutant. This could reduce the apparent increase in $PM_{2.5}$ concentrations and still keep the benefits of increased insulation such as greater thermal efficiency. Assistance with fuel costs whilst encouraging better ventilation behaviour may also increase relative CO_2 emissions undermining reduction policies.

Comparisons between groups in each housing stock using the ANOVA multiple-comparison tests show that below LIT-income owner-occupied and above LIT-income groups have higher levels of outdoor $PM_{2.5}$ in the current housing stock, most likely due to the lower levels of retrofit shown in Figure 2. However, these differences are not seen in the housing stock, following full retrofit. The above LIT-income groups have lower levels of $PM_{2.5}$ from smoking in both the current and fully retrofitted housing stocks compared to all other groups, primarily as a result of a lower number of households with occupants who smoke rather than other factors. $PM_{2.5}$ sourced from cooking is lower in above LIT-income dwellings in both the current and fully retrofitted housing stocks, and is also lower in owner-occupied and private-rented below LIT-income dwellings compared to local-authority and RSL below LIT-income dwellings. These may be a result of higher levels of retrofit in the local-authority and RSL below LIT-income dwellings, but as these differences persist in the fully retrofitted housing stock, it may also be a result of other factors, possibly generally smaller dwelling/kitchen sizes.

Previous studies have indicated that below LIT income populations may be exposed to higher levels of outdoor pollution (Pye et al, 2001; Tonne et al, 2008), while individuals of low socio-economic groups are the most susceptible to negative health consequences from pollution exposure (Deguen & Zmirou-Navier, 2010). Although in all airtightening scenarios the ingress of outdoor $PM_{2.5}$ is seen to reduce, it has been demonstrated that in some UK cities (for example, London), below LIT income individuals live in areas of higher outdoor $PM_{2.5}$ than the general population (Pye et al, 2001). This may act to counter the advantage of the below LIT-income social housing, which were found to have lower levels of indoor $PM_{2.5}$ from outdoor sources, while further increasing the risks to below LIT-income individuals in privately-rented accommodation.

The use of window opening to ventilate dwellings and thereby improve IAQ has been found to be less likely amongst elderly occupants, possibly due to a preference for higher indoor temperatures (Dubrul, 1988; Guerra-Santin et al., 2009). No significant correlation was found between socioeconomic factors and window opening behaviour (DuBrul, 1998). However, it is reasonable to assume that in poorer areas where there is either fear of or actual criminal activity, occupants may be less likely to leave their windows open for security reasons (Fabi et al., 2012). Other factors influencing indoor domestic $PM_{2.5}$ exposure in below LIT income dwellings that require further investigation are the possibility of overcrowding, and multiple smoking occupants which are known to be more prevalent in below LIT income dwelling and add to the $PM_{2.5}$ exposure risk. In addition, the reductions in permeability which decrease air change rates may encourage the transmission of airborne infections and diseases in below LIT income properties (Beggs et al., 2003; Noakes et al., 2006). This is particularly relevant to the private rented sector which is currently growing and is less regulated when compared to Local Authority or RSL dwellings.

It is acknowledged that whilst $PM_{2.5}$ has known negative health impacts, there are other indoor airborne pollutants e.g. volatile organic compounds (VOC), radon and mould which each have associated health effects (Wilkinson et al., 2009, Milner et al., 2014). The trade-off that exists between airtightness and the consequent reduction of ventilation heat loss to achieve GHG reduction goals and public health concerns for IAQ have been previously noted (Wilkinson et al., 2009; Davies & Oreszczyn, 2012). Consequently, an inclusive optimum strategy approach is needed for building ventilation (Jones et al., 2013b) if health is to be a key driver of policy rather than a singular focus on decarbonisation (Crump et al., 2011).

This trade-off between the need for adequate ventilation to improve IAQ, comfort and energy conservation on a limited budget may also add to personal $PM_{2.5}$ exposure profiles for below LIT income occupants. Airtightening in order to conserve energy will likely also have the effect of raising indoor temperatures during summer months (Mavrogianni et al., 2012). This may lead to changes in occupant ventilation behaviour influencing IAQ. This dilemma has been successfully investigated in our study by using coupled thermal/pollutant modelling that is able to account for the increase in outdoor sourced $PM_{2.5}$ found indoors when occupants ventilate their properties when temperatures become uncomfortably high in the summer. It has been also been noted that $PM_{2.5}$ external levels are generally lower in the summer mainly due to metrological impacts, primarily convection and dispersal (McMurry et al., 2004) thereby lessening this effect, however this may not be the case for all pollutant types. In addition, the lower I/O ratio seen in below LIT income housing may also be offset by the location of many such properties in areas with generally higher outdoor pollution levels as previously noted.

5. Conclusions

This study has developed and applied a series of stock model simulations in EP in order to quantify the changes in indoor domestic $PM_{2.5}$ exposure within the English housing stock that occur when buildings are retrofitted with energy efficiency measures. These results have been further subjected to a rigorous statistical analysis to confirm trends of the differences in model estimates. This study highlights the unintended consequence of changes to indoor domestic $PM_{2.5}$ exposures and the health trade-offs that may occur when policies to mitigate climate change do not take into account wider health outcomes. Results indicate that, on average, all types of low income households below the LIT experience greater overall concentrations of $PM_{2.5}$ than those above the LIT and suggest possible social inequalities driven by housing, leading to consequences for health. Below LIT income properties are generally shown to be more vulnerable to increased levels of indoor $PM_{2.5}$ from indoor sources when compared to above LIT income properties, with $PM_{2.5}$ from cooking being the main cause. The increased use of extraction equipment at source could remedy this. Below LIT income housing represents a complex situation with multiple factors - physical, social and economic - influencing occupant exposure to pollutants such as $PM_{2.5}$. Whilst tightening the building envelope to save energy and assist with climate change mitigation objectives is laudable, it is essential that adequate purpose-provided ventilation is provided to avoid the negative health impacts.

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