Determinants of CO Exposure in the English Housing Stock: Modelling Current and Possible Future Risks

"A Report for Gas Safety Trust"

By

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List of Abbreviations, Acronyms and Units

Cin	CO indoor concentration from indoor sources
Cout	Outdoor CO concentration
Cin,tot	Total indoor CO concentration
CO	Carbon monoxide
COHb	Carboxyhaemoglobin
EHS	English Housing Survey
EPC	Energy Performance Certificate
HCR	High Performance Computing Resource (Legion)
.idf	Input definition files
IAQ	Indoor air quality
LHE	Latin Hypercube Experiment
mg/m^3	Milligrams per cubic metre
mg/min	Milligrams per minute
pyDOE	The experimental design package for python
ppm	Parts per million
PPV	Purpose provided ventilation

EXECUTIVE SUMMARY

This report investigates the current distribution of low-level CO concentrations in the English housing stock, and prevalence of dwellings exceeding recommended background exposure levels, using advanced modelling techniques informed by empirical data from a number of disparate sources. By bringing these sources of data together in the models, it is possible to produce new insights into the variation in background CO exposure across dwelling types and geographical location. The model also considers the impact on indoor domestic CO concentrations of the application of energy efficiency measures on the same stock. Although the health effects of long-term low-level CO exposure are still uncertain, this report provides evidence for further discussion and research. There are a number of assumptions listed within the main report, that drive the results. These should be taken into consideration when interpreting outcomes.

Headline Results

1. Using data from the English Housing Survey (EHS) and Energy Performance Certificate (EPC) databases to evaluate the variation in CO exposure risk across the English housing stock, the following trends and observations are noted:

- The majority of homes (85%) are still heated by gas-fired systems
- Flats tend to use other fuel types (primarily for safety reasons)
- Solid fuels are still used in some older homes
- Rural locations tend to have more solid, oil and electric fuel types relative to cities
- Central London has the highest percentage of community heating

2. Results using the modelling techniques, including outdoor concentrations from air pollution models and indoor concentrations from a metamodel based on EnergyPlus building simulation outputs, highlighted the following:

- Cities in general - and London in particular - experience the highest levels of outdoor CO exposures.
- Dwelling type, main fuel type, floor area, how well ventilated a home is act as modifiers to CO exposure from indoor sources, with bungalows, terraced homes, and flats estimated to have higher indoor levels.
- Owner occupied dwellings appear to have generally lower CO exposures from indoor sources when compared to other tenure types.
- Working extract fans significantly reduce CO exposure if used during cooking.

- Urban areas tend to have higher CO exposures due to high outdoor levels and the prevalence of dwelling variants such as flats and terraces that are at elevated risk. Although the modelled outdoor CO concentrations do not have high enough resolution to consider street level exposure, it is likely that small flats in close proximity to busy roads maybe at a particularly high risk.
- Energy efficiency retrofits increase the number of dwellings in England and Wales that exceed EU recommended CO exposures by around 15%. The largest increase is in urban areas.

Recommendations

This covers both suggestions for policy and strategy as well as proposals to modify behavioural influences on exposure.

- Within limited budget constraints, it is suggested that the emphasis for publicity and advice regarding chronic low-level CO exposure be focused on major cities (with London as a starting point as the largest population centre). In particular, advice could be targeted towards occupants of small flats (especially those adjacent to major roads) due to their expected increased exposure.
- That the GST, along with others, push for the addition of purposes provided ventilation (PPV) in any refurbishment strategy (PAS 2030, 2017), as this is essential to prevent an increase in low-level exposure in the English housing stock.
- The continued promotion of advice to owner occupiers and remind private/social landlords to perform regular boiler and gas cooker servicing to help reduce exposure.
- Behavioural changes such as smoking outdoors, using extract fans during cooking, and allowing for additional ventilation through, for example, window opening during smoking or cooking can reduce CO exposure. Education/promotional should continue to focus on these behavioural changes.

Future work should investigate emission rates from different heating fuels and CO-producing indoor activities, and explore the influence of occupant behaviour on indoor CO exposure to refine the model assumptions.

1. INTRODUCTION

The purpose of this report is to investigate the building factors that contribute to and determine low-level CO exposure in the English Housing Stock. We do this by modelling both the current domestic stock and possible future changes in exposure following the application of energy efficiency measures. In this study, faulty equipment has not been modelled, as the emphasis is to investigate the impacts of the building envelop on low-level CO emissions in the general population under normal circumstances.

1.1 Background

Sources of low-level carbon monoxide (CO) exposure in domestic properties include the fuel used in cooking and heating, smoking, and infiltration of CO from outdoor sources. Recent research has highlighted that some occupants in English dwellings may be subject to long-term low levels of CO exposure (Croxford et al. 2008). The health impacts of such exposures are uncertain (Townsend and Maynard. 2002; Clarke et al. 2012). As people in developed countries spend the significant majority of their time in indoor environments, and in particular at home (Kornartit et al. 2010), housing may act as a significant modifier of CO exposure risk and needs to be investigated. Housing characteristics such as building geometry, fabric, energy efficiency and ventilation strategies are known to influence indoor pollution exposure, but their effect on CO exposure are uncertain, as are the impacts of such factors at regional and population level. Low-level CO exposure risk must also be viewed within the context of a changing UK housing stock. It is vital that dwellings undergo extensive retrofitting, with the installation of insulation, more efficient heating systems, and an increase in airtightness in order to reduce greenhouse gas emissions and achieve climate change mitigation targets. The possible reduction in air change rates, unless purpose provided ventilation (PPV) is provided as part of any retrofitting measures, will likely lead to changes in indoor air quality (IAQ). Whilst this may lead to a reduction in infiltration of outdoor pollutants, it will likely result in an increase in the concentrations of indoor sourced pollution including CO. Currently the impacts of such factors are largely unknown, although individual cases show the importance of attention to ventilation following a retrofit (Broderick et al. 2017).

This study seeks to investigate these CO exposures across the English housing stock through an analysis of existing datasets, and modelling indoor concentrations for nationally representative dwellings using a model derived from building simulation software -EnergyPlus (US-DOE, 2013). The model is applied to homes in the English Housing Survey (EHS) and the Energy Performance Certificate (EPC) databases. The interaction of energy efficiency mitigation factors and their influence on low-level CO exposure to the English population are also assessed.

1.2 Aims and Objectives

There exists a gap in understanding of the range of background exposures to CO in England, and how housing may modify exposure risk. The following aims and objectives seek to address this.

Aims: This project aims to improve understanding of the determinants of and variation in CO exposure risk in English homes caused by the stock characteristics. It investigates both the current housing stock and the impacts on CO exposure that canoccur following energy efficient refurbishment.

Objectives: In order to determine this, the following objectives were established:

- Using available national-level survey data as a basis, examine the presence of potential CO emission sources and surveyor-perceived CO exposure risks; and to use the physical characteristics of the dwellings to derive multizone indoor air quality and ventilation models of the housing variants. This will enable exposure levels across the current English housing stock to be quantified. In addition, to investigate the impacts on CO concentrations for a range of energy efficiency and ventilation measures applied to the existing English housing stock (in line with modern building standards) in order to achieve climate change mitigation goals.

- Using the indoor CO concentration estimates, quantify the degree to which housing may modify the risk of low-level CO exposure in dwellings at the population level, across dwelling ages and types, geographical regions, socioeconomic groups, tenures, and other factors. This investigation will help identify housing variants and populations most at-risk of CO exposure, helping to prioritize gas safety interventions.

1.3 Work Packages

In order to address the programmes aims and objectives, the study was divided into 4 work packages/components as shown below.

- **WP1: Background to CO Risk:** Thorough review of the literature to obtain multiple empirical variables and inputs for the modelling components and to direct methodologies.

- **WP2: Building Physics Modelling:** this package involves the construction, testing and running of complex models to represent the whole English housing stock to consider 'whole house impacts' and to predict both current concentrations of CO in the various archetypes and those in a possible future stock subject to the application of energy efficiency measures.

- **WP3: Data Analysis:** comprehensive analysis of both the EHS and EPC datasets to assess homes with characteristics that could result in potential vulnerabilities to low-level CO concentrations. Homes from within these datasets have also been modelled using the tool developed in WP2. Modelling results were analysed to quantify the degree to which the risk of serious CO poisoning varies in relation to building type, regional differences, building type, and tenure in order to highlight the priority risks.

- **WP4: Final Report and Dissemination;** By combining the lines of evidence investigated, this final report provides a detailed analysis of building types and characteristics within the English housing stock and their relationship to risk from low-level CO poisoning. Guidance on exposure and health implications of energy efficiency and ventilation policies and their impact on future CO exposure levels has also been addressed. The outline findings have been accepted as an abstract and were presented at the to the 14th International Conference on Urban Health, Coimbra, Portugal 26-29th September, 2017. A research journal paper is also in the early stages of preparation. It is also the intention that, following the completion of the project, findings will be circulated via various electronic media outlets subject to GST approval.

2. LITERATURE REVIEW

A systematic review was carried out to inform this study. The scope of the literature review was defined and initial keywords established (see Appendix A), which were subsequently used to search for scientific literature in Web of Knowledge (including citation reports which were further investigated via Scopus). 'Grey' literature investigated included the Open Grey data base, European Union and UK Government legislative and policy documents, technical data sheets and specifications, recognised websites (for example from various organisations involved with CO monitoring and measurement) and other web-based articles. The search was limited to relevant studies that were published in the English language.

2.1 Health Consequences from CO Exposure

CO is generated as a result of the incomplete combustion of materials containing carbon. Primary sources include fossil fuels such as gas, petrol, diesel fuel and coal as well as biomass burning and tobacco. CO is a colourless, odourless and tasteless gas that has the potential to be fatal to humans at higher concentrations. Of the 4,000 people per year that arrive at accident and emergency departments displaying symptoms of CO poisoning, over 200 are admitted to hospital for treatment as a result of CO poisoning (HM Government, 2011). Figures for total accidental deaths from CO poisoning for 2015-53 occurrences (ONS, 2016), now also show where the secondary cause of death was the toxic effect of CO, which has not always been previously recorded, such that the total number of deaths may have been previously underestimated. However, the true extent of exposure to CO remains unclear, as many more people are thought to have been exposed, but do not necessarily associate their symptoms (such as headaches, sickness and tiredness) with the effect of CO, some of which can also dissipate relatively quickly once they are removed from the source of exposure (Clarke et al., 2012).

Physiologically, CO displaces the oxygen from the haemoglobin in red blood cells to produce Carboxyhaemoglobin (COHb), which is a specific and very sensitive marker, enabling the determination of CO exposure in individuals (Townsend and Maynard, 2002). The adverse impacts of exposure to high levels of CO have been well documented in various studies e.g. Raub et al. (2000), Kao and Nanagas (2006), Cho et al. (2008). These impacts are dependent on the CO concentration in the ambient air, individual susceptibility, and the duration of personal exposure (Feldman, 1998). Particular groups are more susceptible to the impacts of CO including children, the elderly and people with anemia or a history of heart or lung disease (Metra-Martech, 1998). Although the impacts of high concentrations of CO have been recognized for many years, there has been increasing evidence that prolonged exposure to lower levels of CO may in itself have adverse health effects and that chronic poisoning can occur following exposure at high-level ambient concentrations even below the 200ppm 'threshold'. These negative health impacts include cardiovascular and neurophysiological (cognitive) effects (WHO, 1999). COHb levels between 5-20% have been shown to lead to impairment in cognitive function in healthy adults ((Putz, 1997; Amitai et al. 1998; Chambers et al. 2008), while convulsions may occur at COHb levels of 40-60% (Townsend and Maynard, 2002; Hopkins et al. 2006). Cardiovascular impacts have been reported at COHb levels of between 2–5% and include a reduction in the ability to exercise, in those with ischaemic heart disease (Allread et al., 1989; Klienman et al. 1989). However, other studies have shown this effect to occur in healthy individuals with no evidence of underlying coronary disorders (Aronow et al. 1975). It has also been suggested that chronic CO exposure could increase the risk of developing heart failure (Morris et al. 1995; Burnett et al. 1997), and may even contribute to the development of coronary heart disease (Ward et al. 1973; Borland et al. 1983). Some research suggests that long-term neurological effects can also occur (Myers et al. 1998), but this has not been examined in long-term epidemiological studies to date. A more recent study (Croxford et al. 2008) reported an association between neurological symptoms and low-level CO concentrations in the indoor air. Although further research is required, it is possible based on this study that up to 100,000 English homes could have concentrations of CO likely to cause negative health effects when combined with poor ventilation.

2.2 CO Exposure in English Housing

The role of housing as it impacts population exposure to a range of environmental hazards is an important area of research. As with all developed countries, individuals in the UK spend a large proportion of their time (around 90%) in indoor environments (Kornartit et al. 2010). However, a study of activity patterns in Oxford found participants were spending 96% of their time indoors, with 66% of their time spent in their homes (Schweizer et al., 2007), implying that any changes in indoor air quality are likely to have substantial impacts on population health. Two areas that are currently receiving attention are the issues of indoor air pollution and overheating in homes. These two issues are inherently coupled, as warmer indoor temperatures lead to changes in occupant ventilation behaviour, principally window opening in hot weather due to the UK domestic stock being primarily naturally ventilated (Taylor et al. 2015). This in turn results in changes in indoor concentrations of pollutants such as CO, which can potentially have either positive and negative health impacts depending on the direction of change.

In homes without indoor combustion sources, average CO concentrations are approximately equal to average outdoor levels which range between 0.06 and 0.14 mg/m3 (0.05–0.12 ppm) (WHO, 1999). Research in a small study of UK homes found a mean unadjusted value of ambient CO in the kitchen of 3.5 mg/m3 (3.1 ppm) (IEH, 1998). Passive cigarette smoke increases the exposure experienced by non-smokers in smoking homes by an average of about 1.7 mg/m3 (1.5 ppm) and use of a gas cooking range at home by about 2.9 mg/m3 (2.5 ppm) (WHO, 1999). The possible values from different sources are shown in Table 1.

Table 1 Typical upper limits of CO concentrations with different source scenarios.

Scenario	Concentration in mg/m^3
Non-smoking home with no gas	Up to 3.5
Non-smoking home with gas	Up to 6.0
Smoking home with no gas	Up to 5.2
Smoking home with gas	Up to 7.7

Based on data from IEH, 1998 and WHO, 1999.

However, in homes with faulty or unvented combustion appliances, ambient levels can exceed 110 mg/m^3 (100 ppm), leading to COHb levels in excess of 10% with continued exposure (Raub et al., 2000; WHO, 2010), whereas the normal carboxyhaemoglobin (COHb) level is around 0.3–0.7% in non-smokers and 4% in smokers (Whincup et al., 2006). At these very high levels, studies suggest a risk of adverse cardiovascular events and clinical impairment of cognitive and motor functions (Lambert, 1996). The World Health Organisation (WHO) (WHO, 2010) provides information on suggested maximum concentrations of CO in domestic indoor environments, linked to exposure times for occupants suffering from cardiovascular disease (CD) as seen in Table 2.

Table 2 Suggested maximum CO concentrations with time.

CO Concentration (ppm)	Suggested Maximum period
81.1	15 minutes
28.4	1 hour
8.11	8 hours
5.68	24 hours

WHO (2010) guidelines for maximum indoor exposures over various time frames.

However, these guidelines are in contrast to the British CO alarm standards (BSI, 2013a), which require a concentration above 50ppm for 90 minutes, prior to the activation of an audible alarm. The reason for this difference is that the BSI suggest that below 50ppm, the COHb levels would not be sufficient to produce severe health effects, whilst recognising that some individuals are susceptible to CO poisoning at lower levels (BSI, 2013b). Some monitors have visual displays, but do not alert the user to chronic lower levels that may be harmful in the long term. As CO is a colourless, odourless gas, this leaves occupants with no way of knowing whether they are exposed to hazardous levels without the presence of an alarm.

Although there is an extensive scientific literature and publicly available information on CO poisoning, material on the extent and the main determinants of personal CO exposure in the English population is still very limited. Early CO exposure studies suggested that the main indoor sources are unventilated gas heaters, gas cookers and cigarette smoke, which all make important contributions to CO exposure (Cox et al, 1998), while the contribution of outdoor sources is modest, even where the properties are close to outdoor sources such as transport (Shaper et al. 1981). However, despite there being a wide usage of gas heating and cooking in the English population there is little information about the levels of COHb prevalent in the English population and its causes (Townsend and Maynard, 2002). Consequently, the proportion of homes in which there is a significant risk of CO poisoning remains unclear, despite preliminary work by Croxford et al. (2008). Reducing risk by addressing CO emission sources, such as poor gas appliance installation, may be achieved by regular servicing, awareness of the dangers of CO, and knowledge of how to use appliances correctly. However, the impacts of modifying factors on exposure, such as housing characteristics, location, the presence of potential CO sources, occupant behaviors (including ventilation and CO-generating activities), and occupant demographics are as yet uncertain. As a result, there remains a major gap in knowledge that could help understand which buildings and occupants are at greatest risk, and what advice or measures are most cost-effective in providing protection to occupants.

CO exposure risk must also be viewed within the context of a changing UK housing stock. Housing is responsible for one quarter of the UK total end-user CO_2 emissions, with over half of this produced from space heating (DECC, 2014). Motivated by ambitious targets to reduce CO_2 emissions by 80% from 1990 levels by 2050, concerns over fuel poverty and energy security, and in response to the EU Energy Performance of Buildings Directive (EPBD), there is an urgent requirement to make major improvements to the energy efficiency of both new and existing domestic buildings over the coming decades (HM Government, 2010; EU, 2011; DECC, 2014). With existing housing projected to account for approximately 70-80% of the housing stock in 2050, (Palmer and Cooper, 2011), such proposals suggest that these dwellings should undergo extensive retrofitting, with the installation of insulation, more efficient heating systems, and an increase in airtightness (DECC, 2012). Although 'Brexit' has called the pace of these changes into question, similar policies must be implemented in the future to meet the UK's legally-binding commitments to reduce emissions. Future changes in indoor CO exposure can be brought about by for example; energy efficiency improvements increasing airtightness in order to reduce ventilation heat losses. This reduces air change rates in homes where there may be insufficient PPV, particularly following refurbishment schemes. Such alterations to the building envelope will inevitably lead to changes in indoor air quality including CO concentrations, which now must urgently be taken into account in any strategy to identify and reduce possible negative health impacts from CO. The authors could find no evidence in the literature of studies evaluating CO exposure in prior to and following retrofit, meaning there is little empirical data available to support the Gas Safety Trust's objectives as stated in its updated strategy 'Exploring the impact of modern building standards on indoor air quality'.

3. METHODOLOGY

Using advanced modelling techniques with empirical data sources, wherever possible, this project aims to improve understanding of the determinants of and variation in CO exposure risk in English homes, caused by building factors both currently and in a possible future stock following energy efficient refurbishment. In subsection 3.1, we review available information on the emission rates of CO from various indoor appliances and activities. In subsection 3.2, the EHS and EPC datasets are described. These datasets have been used to identify homes that may be more vulnerable to higher CO concentrations. Section 3.3 describes the building physics modelling using EnergyPlus and the development of the metamodel which enables large-scale building stock models to be performed. Finally, the methods used for the application of the metamodel to these large-scale datasets (stock modelling) are described in subsection 3.4. An overall picture of the analysis performed is shown in Figure 1.

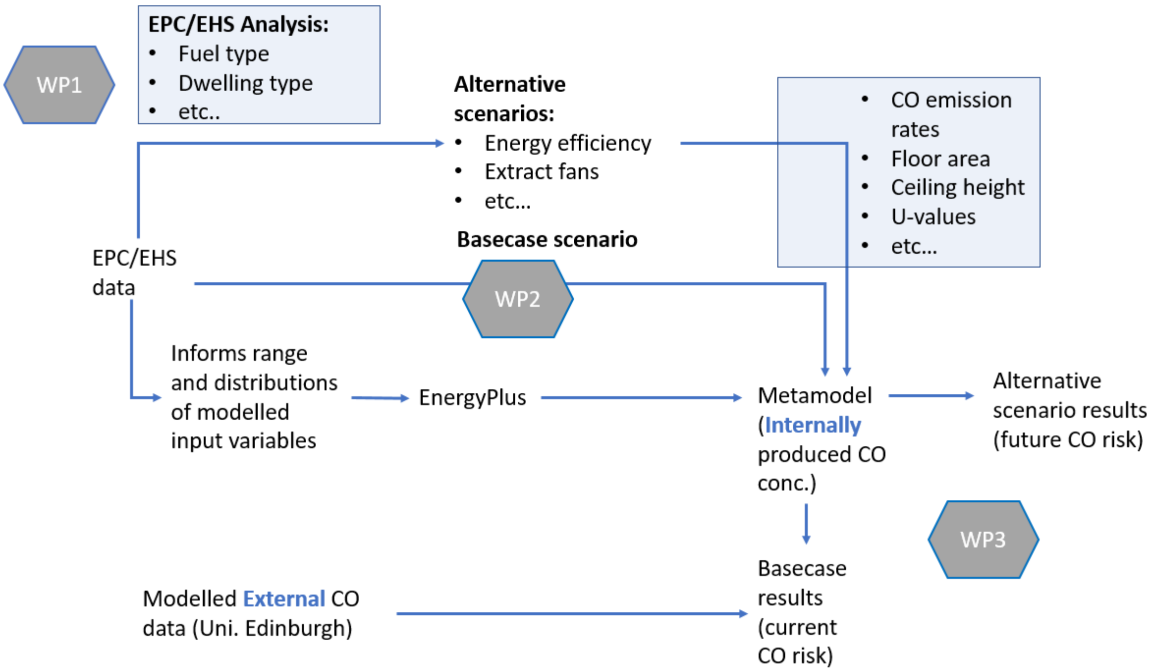

Figure 1 Schematic showing the overall structure of the analysis with the key datasets and modelling tools shown.

3.1 CO Sources

The indoor CO concentration may be assumed to be a function of indoor and outdoor concentrations as seen in Equation 1:

$$C_{in,tot} = C_{out} + C_{in}$$ **Equation 1**

Where: $C_{in,tot}$ is the total indoor concentration, C_{out} is the indoor concentration of CO from outdoor sources, and C_{in} is the indoor concentration from indoor sources. Due to the low reactivity and deposition of CO, *Cout* is equivalent to the ambient outdoor concentration, and therefore does not have to be explicitly modelled but may be derived using outdoor modelled data.

3.1.1 Indoor Sources

The major sources of indoor emissions include cooking and heating systems (including faulty appliances/flues), burning fuels and environmental tobacco smoke (Croxford, 2007). However, if required for future investigation the models can be adapted to account for extreme events as long as the emission rates from faulty equipment are available.

In order to inform the building physics modelling, low-level CO emission rates were investigated. The emission rates cited here are based on empirical measurements. Following a thorough examination of various sources of literature for CO emission data, it was found that the PANDORA database with over 9000 pollutant emission rates, (Abadie and Blondeau, 2011) contained the most robust source data for gas ovens and heaters, having been conducted in chamber experiments, whilst empirical data for cigarette and stove emissions were sourced elsewhere (Aviado, 1990; Dimitroulopoulou et al. 2006). Table 3 lists the potential sources in the indoor environment, their range of emission rates, and original data sources.

Table 3 Sources of CO in the home and their emission rates

Source	**Emissions range**		**Original references**
Cigarette smoking	25-108 mg per cigarette smoked		Aviado, 1990; Dimitroulopoulou et al. 2006
Cooking Gas: Stove	Low	9.0 - 30.0 mg/min	Dimitroulopoulou et al. 2006
	Medium	10.8 - 36.0 mg/min	
	High	12.5 - 58.7mg/min	
Cooking Gas: Oven	NG:FCR: 8400 kJ/h - Mixing Fan ON	Mean: 31.6 mg/min	Traynor et al. 1982
	NG:FCR: 8400 kJ/h - Mixing Fan OFF	Mean: 31.6 mg/min	Traynor et al. 1982
	NG:FCR: 18000 kJ/h, 200°C	Mean: 45.0 mg/min	Borrazzo et al. 1987
	NG:FCR: 9000 kJ/h, 200°C	Mean: 5.0 mg/min	Borrazzo et al. 1987
	NG:FCR: 9600 kJ/h, 260°C	Mean: 5.3 mg/min	Borrazzo et al. 1987
	NG:FCR: 9200 kJ/h 260°C	Mean: 30.7 mg/min	Traynor et al. 1982
Well-tuned Un-Vented Gas Space heater	NG:FCR = 12660 kJ/h	Mean: 24.1 mg/min	Girman et al. 1982
	NG:FCR = 16880 kJ/h	Mean: 46.4 mg/min	Girman et al. 1982
	NG:FCR = 21100 kJ/h	Mean: 7.6 mg/min	Girman et al. 1982
	NG:FCR = 31650 kJ/h	Mean: 9.5 mg/min	Girman et al. 1982
Defective Cooker	Excluded*		
Defective Heater	Excluded*		
Defective Flue	Excluded*		
Incense	Excluded		

*As the scope of this project considers the impact of building factors on low–level exposure, extreme events are excluded. However, due to the flexibility of the modelling this could be a subject for future study.

The schedule of smoking and cooking has been taken from previous studies into indoor air pollution in English dwellings (Shrubsole et al., 2012; Hamilton et al.,2015; Taylor et al., 2016) as shown in Table 4. Boilers are assumed to operate when heating is on, in this case from 6am to 9am in the morning and 4pm to 11pm in the evening during heating season (1st October to 30th April). Each emission source has a time-based schedule of activity associated with it in modelling scenarios. In the absence of empirical data, these are activity-time series based around assumed normal behaviour.

Table 4 Schedules for CO producing activities

Source	Schedules	Room	Reference
Cooking	Cooking for 30 mins morning, lunch and evening	Kitchen	Shrubsole et al.2012
Boilers/heaters	From 6am to 8am in the morning and 5pm to 9pm in the evening (on weekdays) and 7am-11pm (on weekends) during heating season (1st October to 30th April).	Living room	Assumed, based on heating season
Smoking	Smoking is indirectly added using the kitchen and living room emission schedules. An hourly time fraction for smoking is applied to the emission rate (e.g. 5/60 if occupants smoke for 5 minutes each hour). The rationale behind this being that smoking occurs on timescales (~5mins) much shorter than the EnergyPlus output time-step (1 hour) and so can be absorbed by other schedules.	Living room	Shrubsole et al.2012

3.1.2 Outdoor Sources

There are a number of outdoor sources of CO that contribute to background exposure, including transport and emissions from fossil fuel-burning machinery. Modelled hourly outdoor CO concentrations across the UK were obtained from researchers at the University of Edinburgh. Concentrations across the UK were simulated in a 1km x 1km grid by the EMEP4UK regional chemistry transport model; see Vieno et al. (2016), and references therein for a full model description. This data was aggregated into the maximum of the rolling 8-hour average CO concentration over the course of the year, defined by the EU as the maximum allowable exposure limit. The outdoor levels were mapped using ArcGIS as shown in Figure 2.

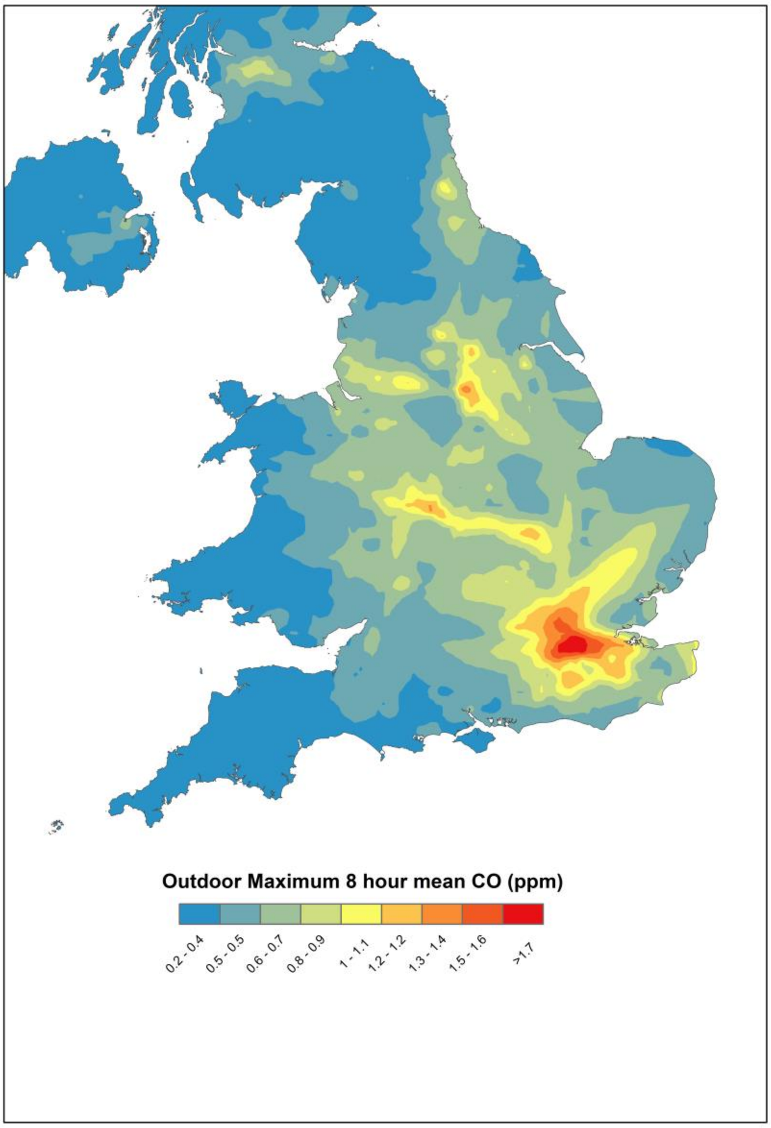

Figure 2 Outdoor annual maximum 8-hour mean CO concentration (ppm) from modelling.

3.2 Analysis of Housing Stock Datasets for CO Risk Factors

The *Background and Literature Review* addresses the context to CO exposure risk in England and further searches included: technical information on potential causes and emission rates from different sources. In support of the review, an extensive, analysis of the English Housing Survey (EHS) 2010 database (DCLG, 2011) and the Energy Performance Certificate (EPC) (DCLG, 2017) database was performed. These databases were investigated to determine the availability of data relevant to potential CO exposure risk across the housing stock, and a number of analyses performed to explore the spatial variation in risk factors across different groups and spatial areas. In addition, the databases form the basis for the building physics modelling of the stock.

3.2.1 English Housing Survey

The EHS is a continuous national survey commissioned by the Department for Communities and Local Government (DCLG) that collects information about the population's housing circumstances, and the condition and energy efficiency of housing in England with in-depth information on dwelling and occupant characteristics obtained by trained and qualified surveyors. The EHS has three component surveys: a household interview, followed by a physical inspection and a market value survey of a sub-sample of the properties. The physical survey involves a physical inspection by qualified surveyors of a random subsample of around 8,000 properties per year scattered across England. These are added to the previous year's survey to achieve a sample size of between 10-16,000 for more detailed analysis. The EHS contains data on primary and secondary heating fuels and the presence and working order of extract fans in kitchen and bathrooms. For the EHS, CO relevant data was found to include:

- The main fuel type for heating, including communal systems, gas-fired systems, oil-fired systems, solid fuel-fired systems, or electric systems.
- An assessment of whether repairs are necessary to the boiler system, if present (major repair, minor repair, replace, none, unknown).
- An estimate of the CO exposure risk according to the UK Home Health and Safety Rating System (average risk, extreme risk, lower than average risk, higher than average risk).

The variation in the data was examined by region, dwelling type, tenure, and dwelling age. No data was available in the EHS regarding other gas appliances, such as cookers or gas fireplaces, and so these could not be assessed by this method and are dealt with under Section 3.3.

3.2.2 Energy Performance Certificates

The UK Government has recently released the EPC dataset (DCLG, 2017), which contains address data and dwelling characteristics for over 18 million houses across the UK. The EPC dataset was analysed to examine the spatial variation in risk factors for CO exposure. Here, data related to risk was limited, but included fuel types:

- Connectivity to mains gas (Y/N)
- The main type of fuel used for heating (mains gas, community, electric, wood, coal, LPG, anthracite, oil)
- Any secondary fuels used for heating (as above)

Data may be mapped spatially, for example the percent of dwellings with mains gas connectivity (Figure 3). Data was extracted from the EPC dataset for all buildings, and the fuel types for each building extracted freetext fields describing fuel sources and heating systems. The frequency of different fuel types was calculated for each postcode and Westminster Constituency, and the results mapped using ArcGIS 10.3 (ESRI, 2013).

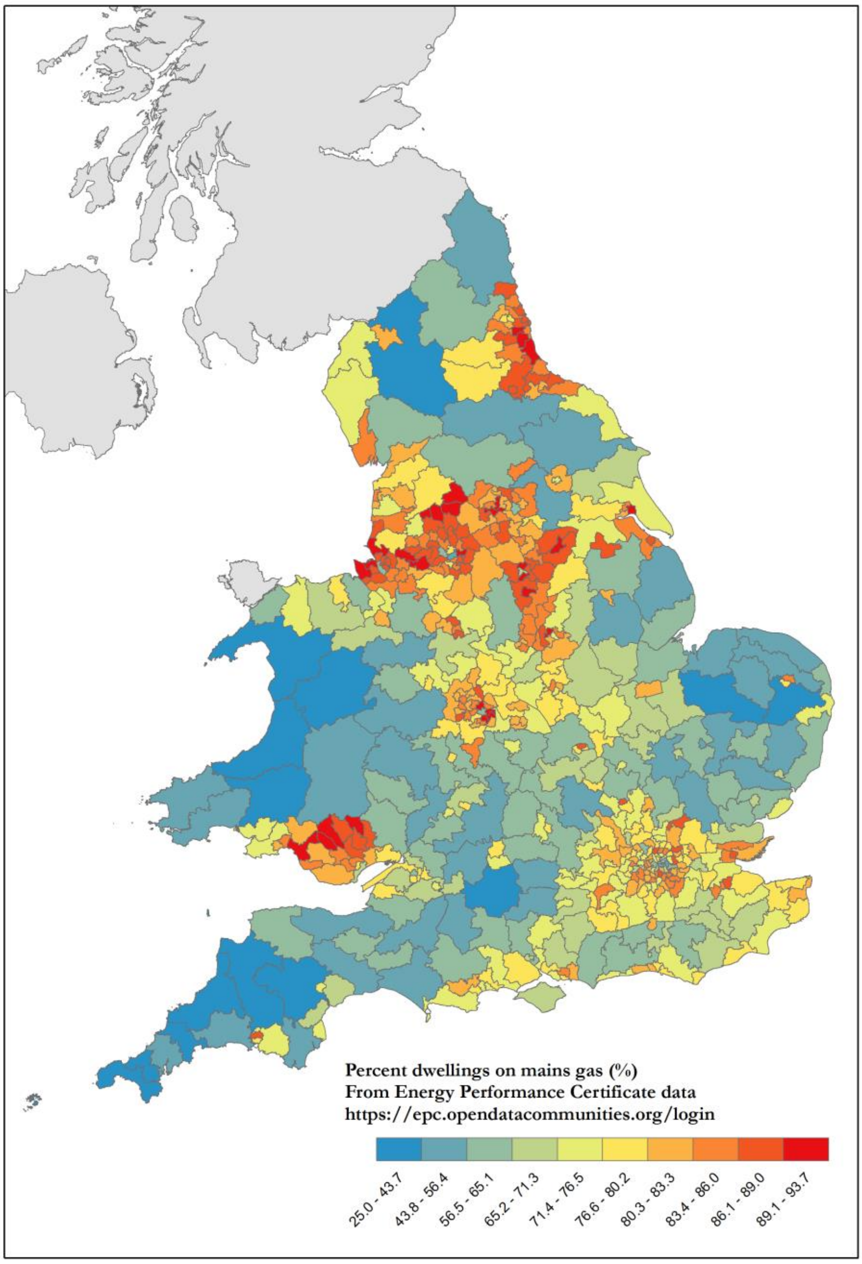

Figure 3 The percent of dwellings connected to mains gas per Westminster constituency, assumed to be the sum of dwellings in the EPC dataset connected to mains gas relative to the total number of dwellings within the constituency, as per the 2011 Census.

3.3 Building Physics Modelling

There are a variety of indoor exposure modelling techniques and software available to investigate the impacts of changes in CO concentrations at different scales and levels of accuracy. These range from simple statistical regression and mass balance approaches, to more complex multizone and computational fluid dynamics tools that have large and complex input data requirements which demand greater computer processing time.

To be able to model the substantial number of buildings in the EHS and EPC datasets under current and post-retrofit scenarios, a metamodeling approach was taken. To do this, a large number of models were run using the building physics tool EnergyPlus, and the outputs of these models used to create a 'model of a model', or metamodel. The development of the full metamodel is shown in Figure 4 and involves a number of steps which are outlined here and include: (i) the random sampling of EnergyPlus input parameters, (ii) the generation of EnergyPlus input files, (iii) building physics based simulations, (iv) calculation of the CO output metrics and (v) the training and testing of potential metamodels. These steps are described in detail below.

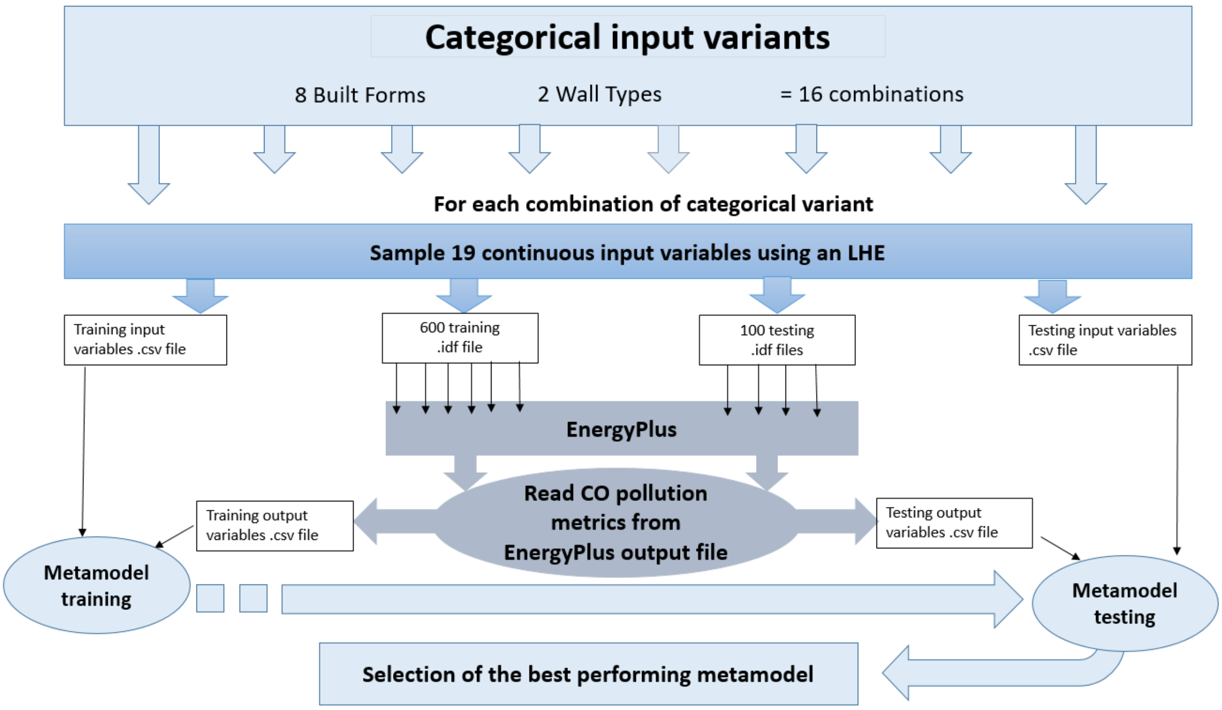

Figure 4 Flow diagram for the development of a national CO model using the High Performance Computing (HPC) resource.

The first step involves the generation of EnergyPlus input definition files (idfs). For each combination of categorical variant, independent sets of 600 and 100 idfs are produced for training and testing, respectively. Nineteen continuous building and occupancy relevant variables are sampled using a Latin hypercube experimental (LHE) design for each idf. The idfs are then simulated with EnergyPlus in parallel sets of 25 simulations. Following this, the relevant Carbon Monoxide exposure metrics are calculated from the EnergyPlus output files. Finally, the training and then the testing of metamodels is performed. All model development steps are performed in parallel for each combination of the categorical variants using UCL's High Performance Computing (HPC) resource, Legion. The steps are described in detail below

3.3.1 EnergyPlus Models

Previous research has shown that indoor pollutant concentrations in the English housing stock can be influenced by for example: building geometry and orientation (Shrubsole et al. 2012); fabric characteristics, natural ventilation and PPV (Hamilton et al. 2015; Shrubsole et al.2015a; Taylor et al. 2015); occupant behaviour (Shrubsole et al. 2012; Symonds et al. 2016) and climate adaptation and mitigation measures (Milner et al. 2014). Multizone models enable the modelling of multiple indoor source types and characteristics, with detailed scheduling of source-based activity allowing changes in source emission rates over time. Models can be easily adjusted to simulate changes due to the application of a range of energy efficiency measures, ventilations strategies linked to occupant behaviour and varying external conditions (Dimitroulopoulou et al., 2001; Glytsos et al., 2004).

Due to the nature of this study, its scope, scale, objectives and the level of complexity required, a dynamic building simulation model, 8.6 (US-DoE, 2013), was used. EnergyPlus is capable of modelling – for example – multizone natural ventilation, contaminant transport, indoor temperatures, and energy use in buildings in response to transient external weather files. It has been used in previous studies to model indoor air pollutant levels (Taylor et al. 2014, 2015; Shrubsole et al. 2015b) for dwellings representative of the English housing stock. In the UK housing stock, buildings are predominantly naturally-ventilated. To model this, simulations assume that dwelling permeability is provided by adventitious openings (gaps and cracks) in the external walls, floors and roofs, with gap size proportional to facade area and assuming a crack is situated at the base and top of each wall (Orme and Leksmono, 2002). In addition, window-opening behaviour is modelled when indoor temperatures exceed 22°C.

Eight archetypes representative of the English housing stock derived in a previous project (Taylor et al., 2016), were used to represent the dwelling built forms, including: End terrace, mid terraces, semi-detached, detached, bungalow, converted flats, low-rise purpose built flats, and high-rise purpose-built flats (shown in Appendix B). For each of these built form variants, nineteen building parameters were randomly selected using a Latin hypercube method, including building fabric u-values, permeability, floor size, ceiling height and occupancy related parameters as shown in Table 5. In each case, the selection of these parameters was informed by available housing stock data including the measured distribution of building fabric air permeabilities (Stephen, 2000), and geometrical and fabric data from the EHS (DCLG, 2011).

For this study, indoor sources of CO were modelled, including those from cooking (kitchen), heating (living room), and from smoking (living room). Here, the CO emission rate of the activity is based on ranges of all-pollutant emission rates obtained from the literature (see Table 3), and operation of the extract fan during cooking (no extract fan or building regulations extract fan) were also randomly selected. The schedule of pollutant-generating activities is based on previous studies, summarised in the literature review (see Table 4). Emissions from boilers were assumed to occur when the boiler was operational during heating hours (September-May, 6-8am, 4-12pm) when temperatures are below the thermostat setpoint of 22°C.

Table 5 Model input parameters sampled within the LHE with range and distributions used.

Parameter	Range	Distribution
Wall U-value	0.15-2.55 W/m^2K	U
Roof U-value	0.10-2.25 W/m^2K	U
Window U-value	0.85-4.80 W/m^2K	U
Floor U-value	0.15-1.30 W/m^2K	U
Fabric air permeability	0-∞ $m^3/h/m^2$ @ 50 Pa	TN(μ=20,σ=10)
Orientation	0-360°	U
Terrain Type	City/Urban/Rural	Discrete
Floor area scale factor	0.65-2	U
Floor height	2-3m	U
Glazing faction	0.1-0.6	U
Occupant window opening temperature threshold	10-∞°C	TN(μ=24,σ=5)
Occupant thermostat setting	15-26 °C	TN(μ=22,σ=3)
Internal gains scale factor	0.35-1.9	U
CO emission rate (kitchen)	0.05-0.70 $\times 10^{-6} m^3/s$	U
Extract fan eff. (kitchen)	0-1	U
CO emission rate (liv)	0.05-1.0 $\times 10^{-6} m^3/s$	Power law

EnergyPlus simulation input definition files (idf) were generated using a UCL in-house tool, EnergyPlus Generator 2 (EPG2); written using the Python programming language (Van Rossum 2001). EPG2 is designed for the batch generation of building input files based on user-defined variables. The tool is able to generate a large number of idf files rapidly. Producing idf files in parallel for each building archetype also speeds up processing. The EPG2 tool is supplemented with the pyDoE (Baudin, 2015) package to enable the selection of input variable values based on a Latin Hypercube Experimental (LHE) design. LHE is a sampling method that allows for the random generation of various parametric values, according to underlying distributions and ensures that similar runs are never repeated (Tang, 2012). An advantage of the LHE sampling technique is that different distributions can be used for different input variables. If an input parameter's range and shape of probability distribution is well known, a specific distribution can be chosen for sampling. Otherwise, a uniform distribution or a normal distribution with a large standard deviation is chosen. The variable ranges are designed to be large such that the entire existing English housing stock database and future retrofit scenarios can be represented.

A total of 11,200 EnergyPlus idf files were created and simulated on the University College London (UCL) high performance computing (HPC) resource, Legion. This resource has 7,500 CPU cores, enabling multiple process steps to be run in parallel, substantially reducing processing time. This enabled the 11,200 building physics simulations to be run within about 10 hours by parallel processing 448 sets of 25 simulations, outputting hourly indoor CO concentrations in the living room and kitchen for the year-long simulation period. EnergyPlus simulations were run using a weather file representative of the typical conditions in Birmingham, assumed to represent the 'average' weather conditions across England and Wales. A 2030 medium CO_2 emissions projection weather file was used to represent average conditions over the coming 20-30 years (time scales for housing stock retrofit).

The hourly indoor CO concentrations from EnergyPlus simulations were used to calculate CO exposure metrics, including the 8-hour maximum value in the kitchen and living room over one year using programming language Python (Python, 2017). For the purpose of this study we have used the 8-hour rolling mean to output CO concentrations in line with maximum values from the WHO (WHO, 2010), as shown in Table 3.

3.3.2 Metamodel Development

The metamodeling framework was then created to allow the rapid estimation of CO exposures for both the existing English housing stock and a possible future stock, subject to a range of energy efficiency and ventilation scenarios. This enables the time-consuming building physics model to be replaced with a quick, less computationally intensive approximate model that also allows sensitivity analysis and multi-criteria optimization to be carried out. Such methods have been shown to give reliable estimates of complex models in previous studies using EnergyPlus (New et al. 2010; Van Gelder et al. 2014, Symonds et al. 2016).

The metamodeling framework was developed using the inputs (Table 5) and CO exposures output by EnergyPlus models. As stated previously, a set of 600 simulations are used for the training of each individual metamodel until convergence. Artificial Neural Network (ANN) models were constructed using the Python-based pyBrain tool (Schaul et al., 2010). A set of ANN architectures were used in training with the number of layers (1-2) and neurons (4-20) varied for each built-forms metamodel. An independent sample of 100 EnergyPlus simulations was used to test the performance (R^2) of each trained metamodel. The best performing metamodel for each built form/wall type was selected for inclusion in the metamodeling framework.

3.4 Stock Modelling

The EHS and EPC datasets were used as inputs and processed through the metamodel framework (described in subsection 3.3.2) which allows the indoor CO concentrations to be predicted for individual dwellings in the English stock (EHS) and English and Welsh (EPC) datasets based on the building input parameters.

3.4.1 Inputs from English Housing Survey Data

A parameterised version of the EHS is available that uses data within the EHS to estimate building fabric and air tightness characteristics (Hughes et al., 2012), according to methods in the UK Governments Standard Procedure for Energy Rating in Dwellings (SAP) (BRE, 2009). This dataset was supplemented by EHS data on the primary heating fuel within each dwelling, described in Table 6, and the presence of a working extract fan in the kitchen. From research on CO emission rates for different fuels, each heating fuel was assigned a CO emission rate. There was no data on the venting of emitted CO, and so it was assumed that 90% of the emitted CO was vented, while 10% remained in the property. In the modelling this was achieved by cutting the emission rates in Table 6 to 1/10th of their value. As the smoking and cooking, emission rates were taken from Table 3. Due to a lack of available information on smokers and stove types, and to illustrate theoretical differences across the stock due to dwelling characteristics, smoking and gas cooking was modelled in each EHS dwelling. Heating, smoking, and cooking were modelled independently to demonstrate the CO concentration by source, as well as combined.

Table 6 CO emission rates for different fuels

Fuel/Heating type	Estimated emissions rate (m^3/s)	Reference
Gas (mains)	2.2E-7	Caceres T., Indoor house Pollution: Appliance Emissions and Indoor Ambient Concentrations
Bulk LPG or Bottled gas – propane	1.2E-7	Caceres T., Indoor house Pollution: Appliance Emissions and Indoor Ambient Concentrations
Heating oil	2.3E-8	Caceres T., Indoor house Pollution: Appliance Emissions and Indoor Ambient Concentrations
House coal, Wood or Solids	4.0E-5	Tissari J., Fine Particle and Gaseous Emissions from Normal and Smouldering Wood Combustion in a Conventional Masonry Heater
Community or electric	0	NA

The derived metamodel was used to estimate indoor CO concentrations for each building in the parameterised EHS according to the building characteristics, activity, and the emission rate of the heating fuel used in the dwelling. Additionally, the same stock was modelled following a number of housing retrofits, including draught proofing, insulation, triple glazing (with trickle vents), loft insulation and cavity wall insulation. There is little information available on the effects of retrofits on dwelling permeability, and so for the purposes of this study a complete retrofit is estimated to reduce a dwellings permeability (derived using the SAP methodology) by $5m^3/h/m^2$, to a minimum of $3m^3/h/m^2$ as per Milner et al (2014) and Taylor et al (2015). This represents one of the key assumptions driving the modelling results. The impact of additional insulation on indoor temperatures, and subsequent air buoyancy, is also included in the post-retrofit dwellings. In all cases, the contribution of outdoor sources was ignored as the intention is to demonstrate differences in exposure caused by dwelling characteristics rather than location.

The EHS contains household and dwelling weighting values, which may be used to determine the theoretical variation in the exposure across the English housing stock, as well as between different dwelling types and occupant groups. Descriptive trends across building types were analysed using SAS to demonstrate the variation in exposure across different building types.

3.4.2. Inputs from Energy Performance Certificate Data

The EPC data has been parametrised using the SAP documentation in a manner similar to the EHS. Like the EHS, the EPC dataset contains information indicating the types of fuels used for heating, enabling the identification of houses where CO exposure may be a risk. Unfortunately, it does not contain information on the presence of working extract fans, stove type, or the presence of a smoker. A total of 11 million dwelling in the EPC database had sufficient building information to enable them to be modelled; this included approximately 5.5 million unique building variants. The metamodel was run for the EPC dataset, enabling the calculation of the unique building variants in around 5 hours. The model assumed that extract fans are used when cooking, and fuel emission rates were the same as those used in the EHS model. As with the EHS dataset, the EPC stock was also modelled following complete retrofit, including the addition of insulation, triple glazed windows (with trickle vents), and airtightening of the building fabric by up to $5m^3/h/m^2$.

In addition, the geographic information in the EPC dataset enabled background outdoor concentrations of CO to be included. The outdoor modelled CO concentrations were matched to the closest postcode using ArcGIS 10.3, which was in turn matched to the addresses of dwellings within the EPC database. This enabled the spatial variation in the combined indoor and outdoor contributions to indoor CO to be estimated for individual buildings. The results for individual indoor sources, as well as indoor and outdoor sources, were aggregated at the constituency level and mapped using ArcGIS.

4. RESULTS

4.1 Risk Factors for CO Exposure Across the Current Stock

We begin by showing the survey data relating to CO exposure risk from the EHS and EPC datasets.

4.1.1 EHS

The variation in exposure risk potential due to indoor sources across the EHS can be seen in Figures 5-7. The primary heating fuel in all regions was mains gas, with community and electric systems found in higher levels in London, and a higher number of oil-fired systems in the East. Mains gas was less prevalent in flats that in houses. In these cases, electric or community systems were more common. Electric and community systems were also more common in private rented, local authority, and registered social landlord (RSL) properties. Oil-fired systems were more common in very old dwellings, with newer dwellings having an increased frequency of electric or community heat as the primary means of heating households.

The EHS surveyor's assessment for boiler repairs were very small across the stock, with the majority requiring no action (86%), major repairs (0.05%), minor repairs (1%), or replacement (0.1%) relatively infrequent. The need for boiler repairs or replacement had a small variation by region, likely due to variations in the prevalence of electric or community heat in the housing stock in different locations. As flats were more commonly heated by electric of communal systems, the need for boiler action was reduced amongst these dwelling types. The assessed risk of CO exposure was also very low across the stock, with 95% considered to have an average risk, 9.2% having a lower than average risk, 0.33% having a higher than average risk, and only 0.03% having an extreme risk.

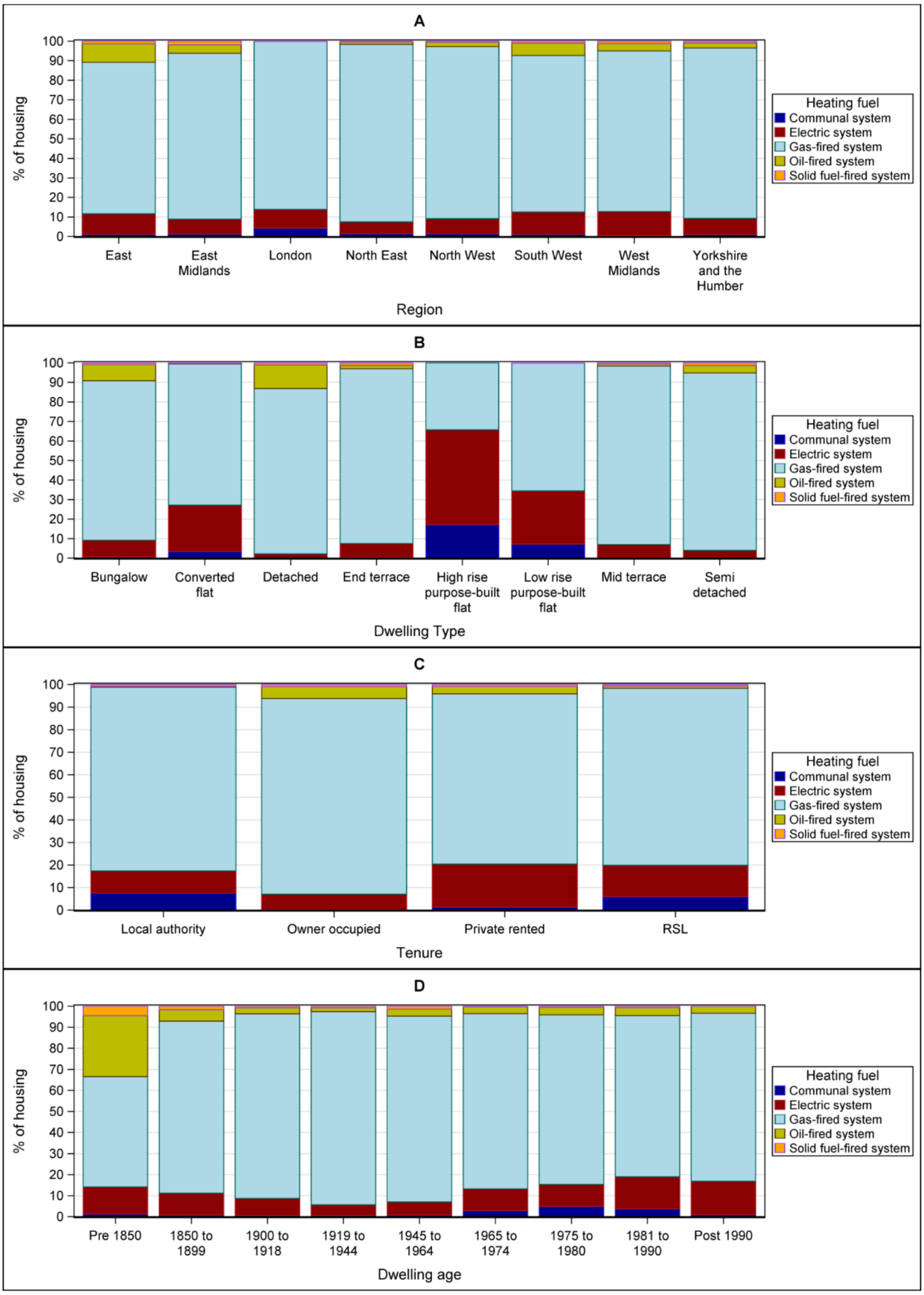

Figure 5 The estimated variation of primary heating fuel used by dwellings in the EHS by (A) Region, (B) Dwelling type, (C) Tenure, and (D) Dwelling age

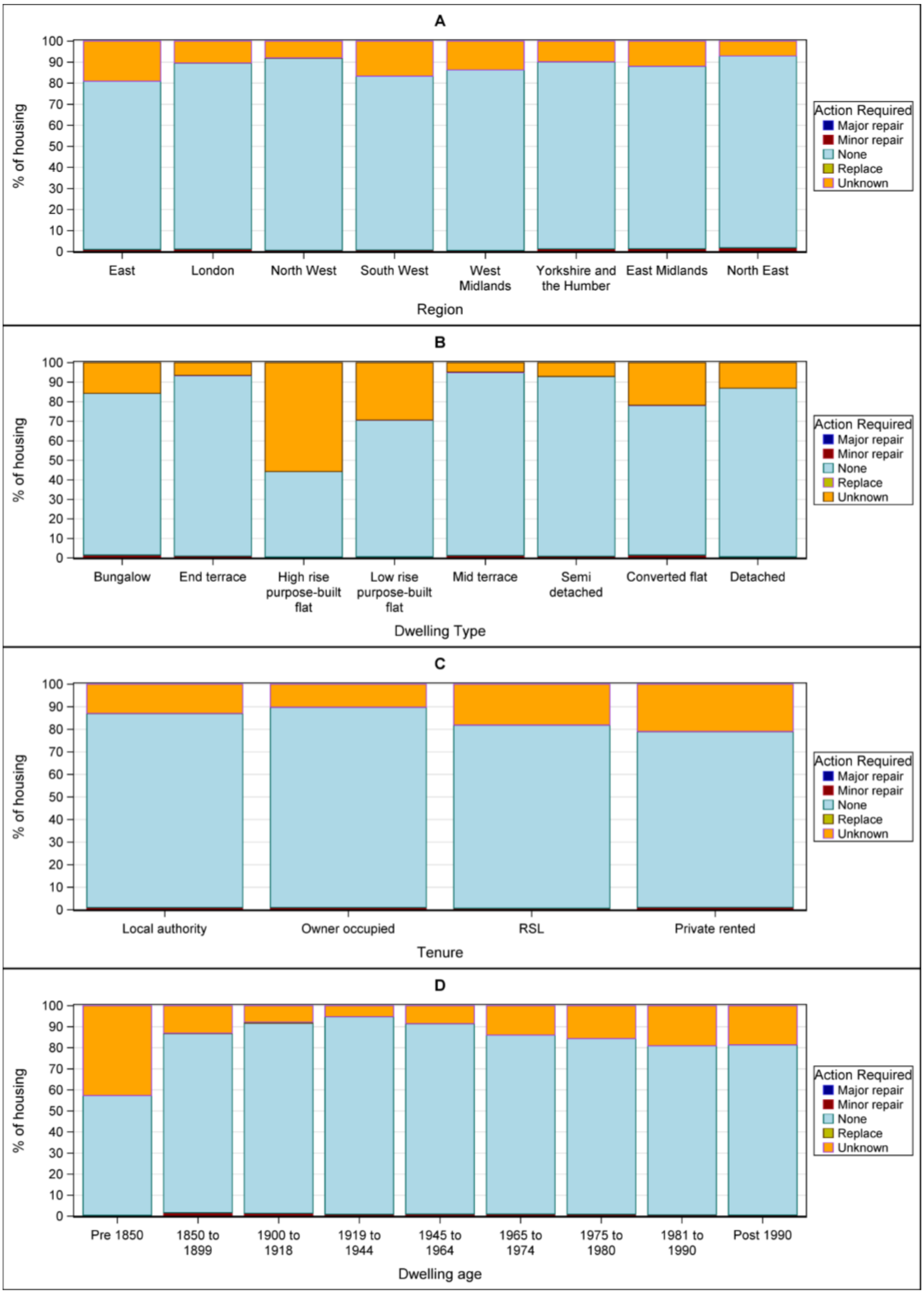

Figure 6 The estimated variation of boiler repairs required for dwellings in the EHS by (A) Region, (B) Dwelling type, (C) Tenure, and (D) Dwelling age

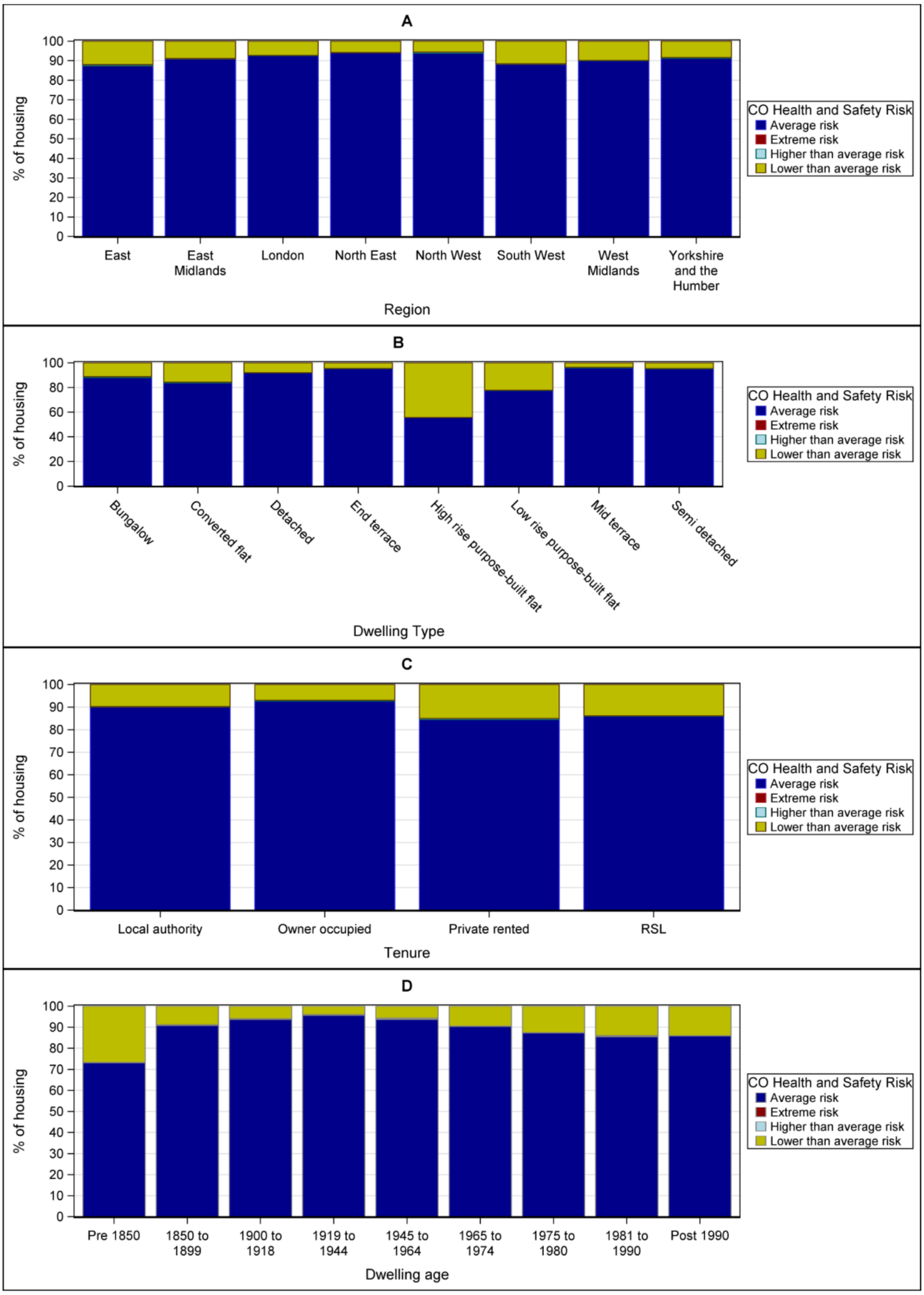

Figure 7 The estimated variation of HHSRS-estimated risk of CO exposure for dwellings in the EHS by (A) Region, (B) Dwelling type, (C) Tenure, and (D) Dwelling age

4.1.2 EPC

The EPC certificate-derived spatial variation in primary heating fuel use - assumed to be an indicator of a source of potential uncombusted gas and therefore CO exposure risk - can be seen in Figures 8-10, while example postcode-level maps can be seen in Appendix C. Results indicate that mains gas is the predominant fuel type for heating across England, with pockets of community heat (London), solid fuel (Wales and Yorkshire), and oil (Wales, Yorkshire, and the East). There is no information on the venting systems used alongside each heating fuel, however heating fuel data is able to indicate the presence of risk within a dwelling.

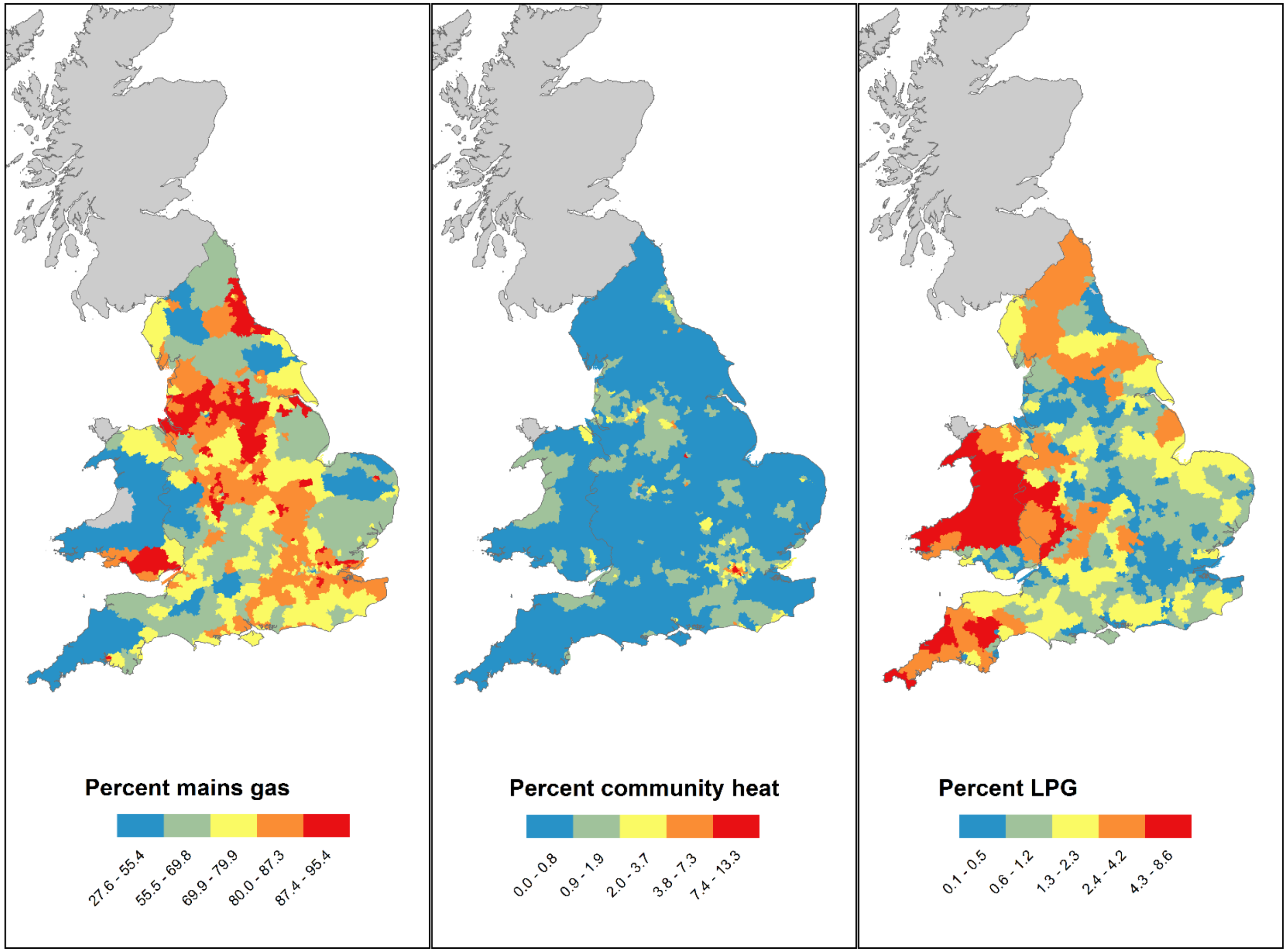

Figure 8 The percent of dwellings with mains gas, community heat, or LPG as the primary heating fuel in each constituency, according to EPC data.

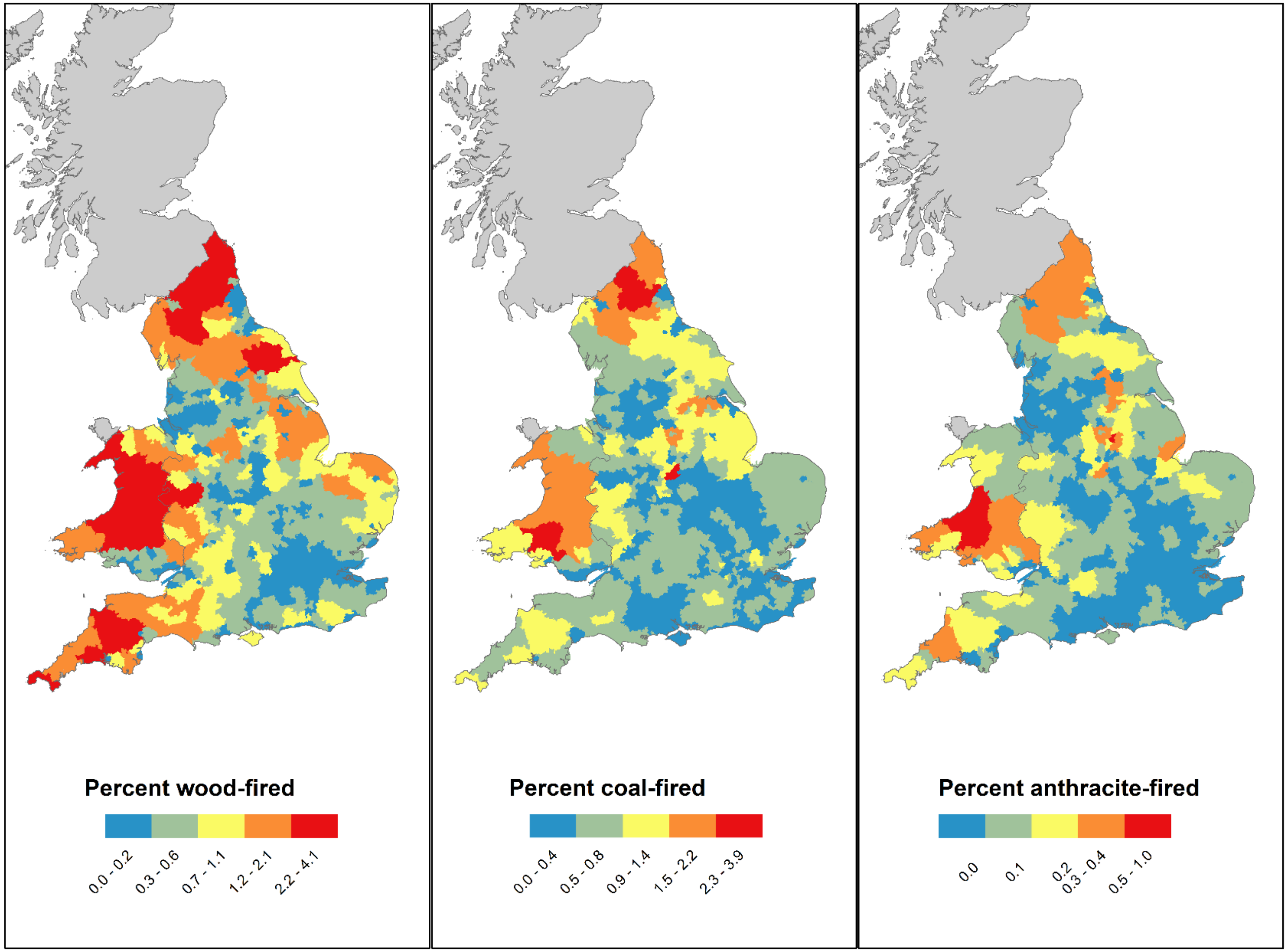

Figure 9 The percent of dwellings with wood, coal, or anthracite and the primary heating fuel in each constituency, according to EPC data.

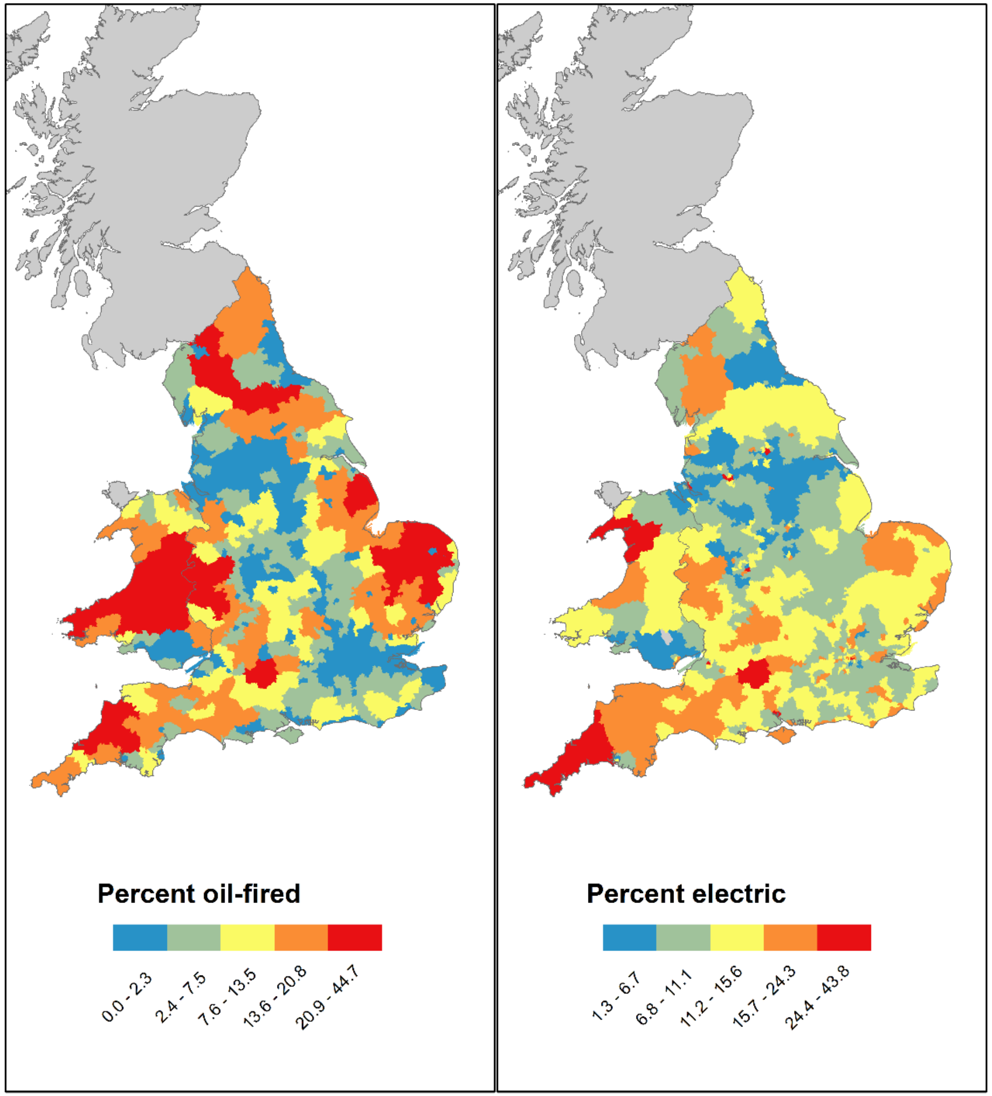

Figure 10 The percent of dwellings with oil or electricity as the primary heating fuel in each constituency, according to EPC data.

4.2 Indoor CO Model Outputs

Outputs from the stock modelling are presented in this section. Graphs are shown separately for each source (cooking, smoking, heating and all) for clarity.

4.2.1 EHS

The application of the metamodel to the EHS shows a variation in concentration across dwelling types (Figure). For cooking, converted flats had the highest levels of maximum 8-hour mean concentration due to: the relatively small kitchen areas; close proximity to neighbouring dwellings who are assumed to be cooking simultaneously; and the relatively small number of working extract fans across this dwelling variant. Low rise purpose-built flats and bungalows are also found to reach relatively high concentration levels. To show the expected variation across building types due to built form, building fabric permeability, and purpose-provided ventilation, this model assumes all dwellings have a gas cooker; in reality, this is not likely to be the case; for example, gas is less common in some older high rise flats, although more recently built flats have gas supply. For smoking and heating, where emission sources were modelled in the living room, maximum 8-hour mean concentration in the living room was highest in bungalows, low-rise flats, mid-terraced houses, and semi-detached properties; as with cooking, this is likely related to the floor area of the room with the emissions, as well as the types of heating systems found in each dwelling type. Following retrofit, indoor concentrations increased moderately in all dwelling variants.

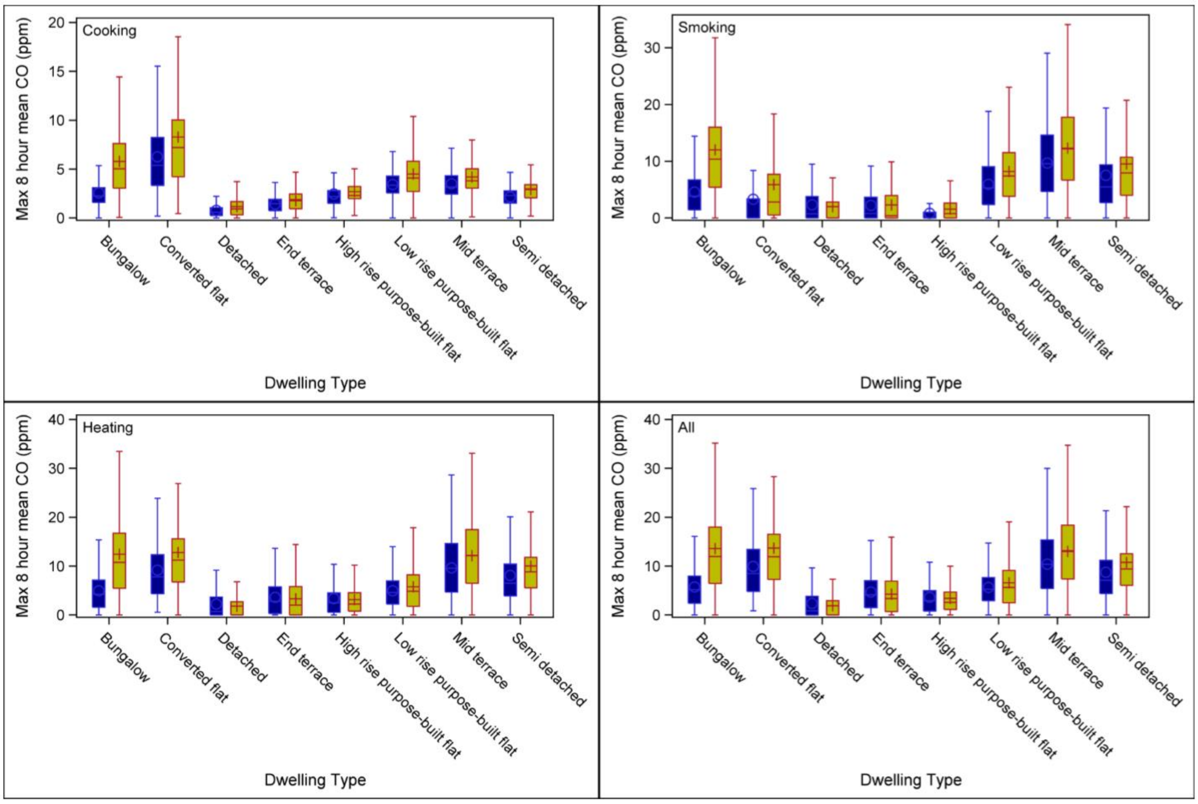

Figure 11 The annual maximum of the 8-hour rolling mean CO concentration (ppm) by dwelling variant for cooking (kitchen), smoking (living room), heating (living room), and all sources (living room) by EHS dwelling type. Blue is modelled under current building stock conditions, while yellow represents a full retrofit.

The importance of functioning extract fans when cooking on CO exposure can be seen in Figure 12. A working extract fan is able to significantly reduce CO exposure during cooking, particularly following building retrofit. This demonstrates the importance of having purpose-provided ventilation during energy efficiency improvements.

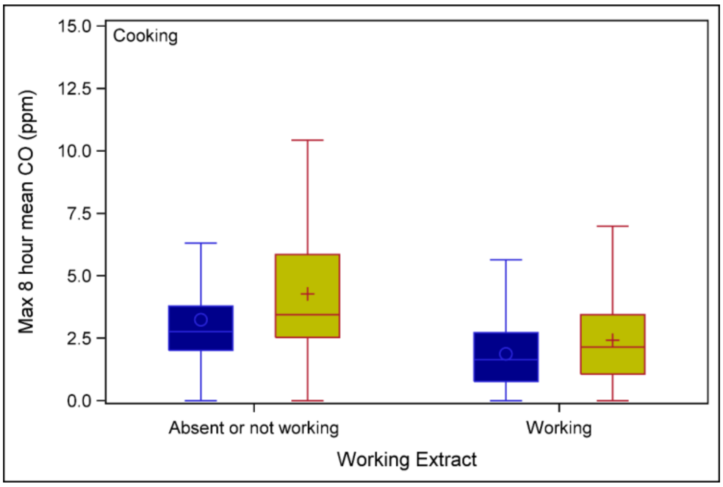

Figure 12 The annual maximum of the 8-hour rolling mean CO concentration (ppm) in kitchens with and without working extract fans. Blue is modelled under current building stock conditions, while Yellow represents a full retrofit.

The variation across dwelling types led to similar trends across tenure groups, with local authorities and private rented dwellings having higher kitchen concentrations during cooking activities (Figure 13). Previous research (Shrubsole et al., 2015b) has suggested that this is likely due to the smaller floor areas in these dwelling types, while there is also a relatively high number of inoperable kitchen exhaust fans in private rented dwellings, which may compound the problem. The results show similar trends for smoking. Regional differences were small (Figure 14), with results suggesting that London dwellings have a moderately elevated risk of cooking CO possibly due to the smaller floor areas and therefore room volumes relative to the rest of the country, while CO from heating systems was estimated to be smaller in London possibly due to the greater number of electrical or community systems relative to other parts of the country.

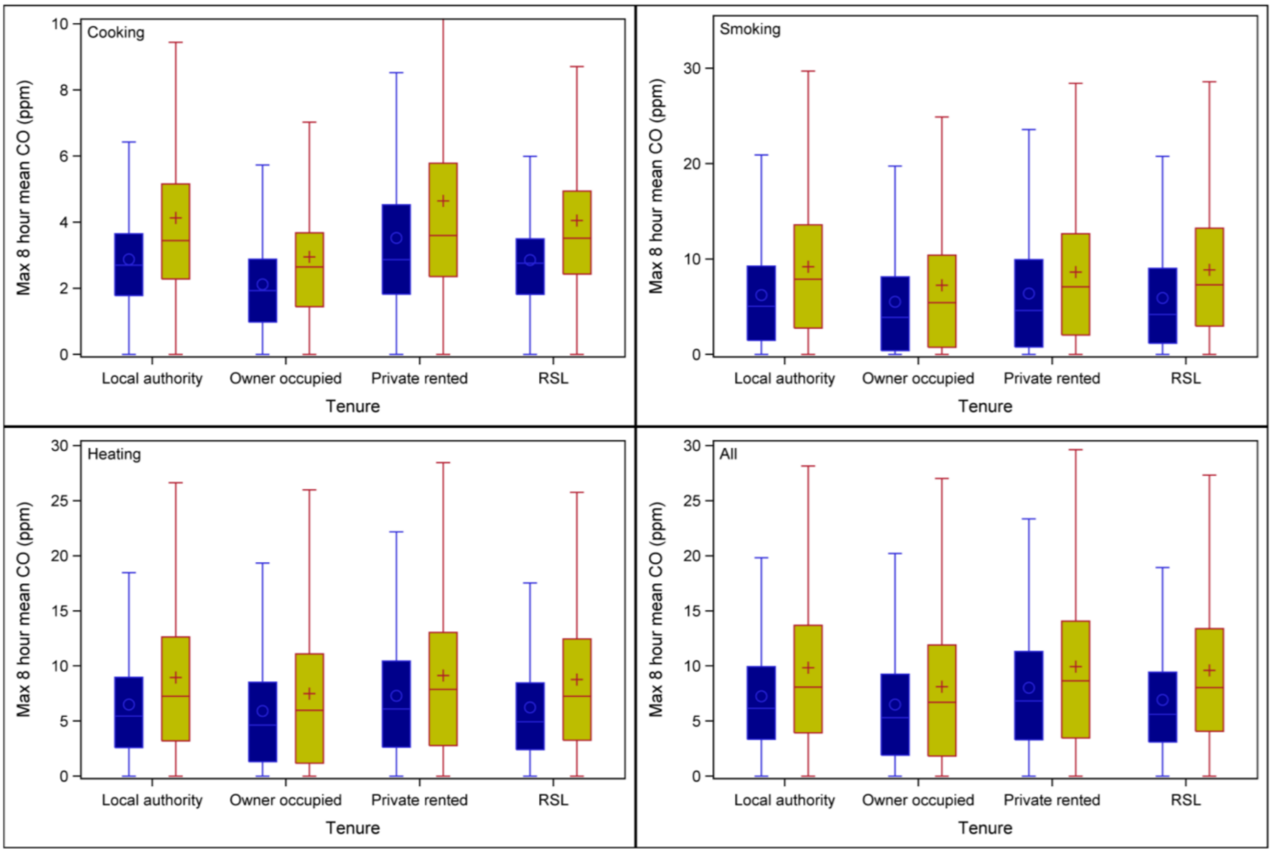

Figure 13 The annual maximum of the 8-hour rolling mean CO concentration (ppm) by dwelling variant for cooking (kitchen), smoking (living room), heating (living room), and all sources (living room) by EHS tenure type. Blue is modelled under current building stock conditions, while yellow represents a full retrofit.

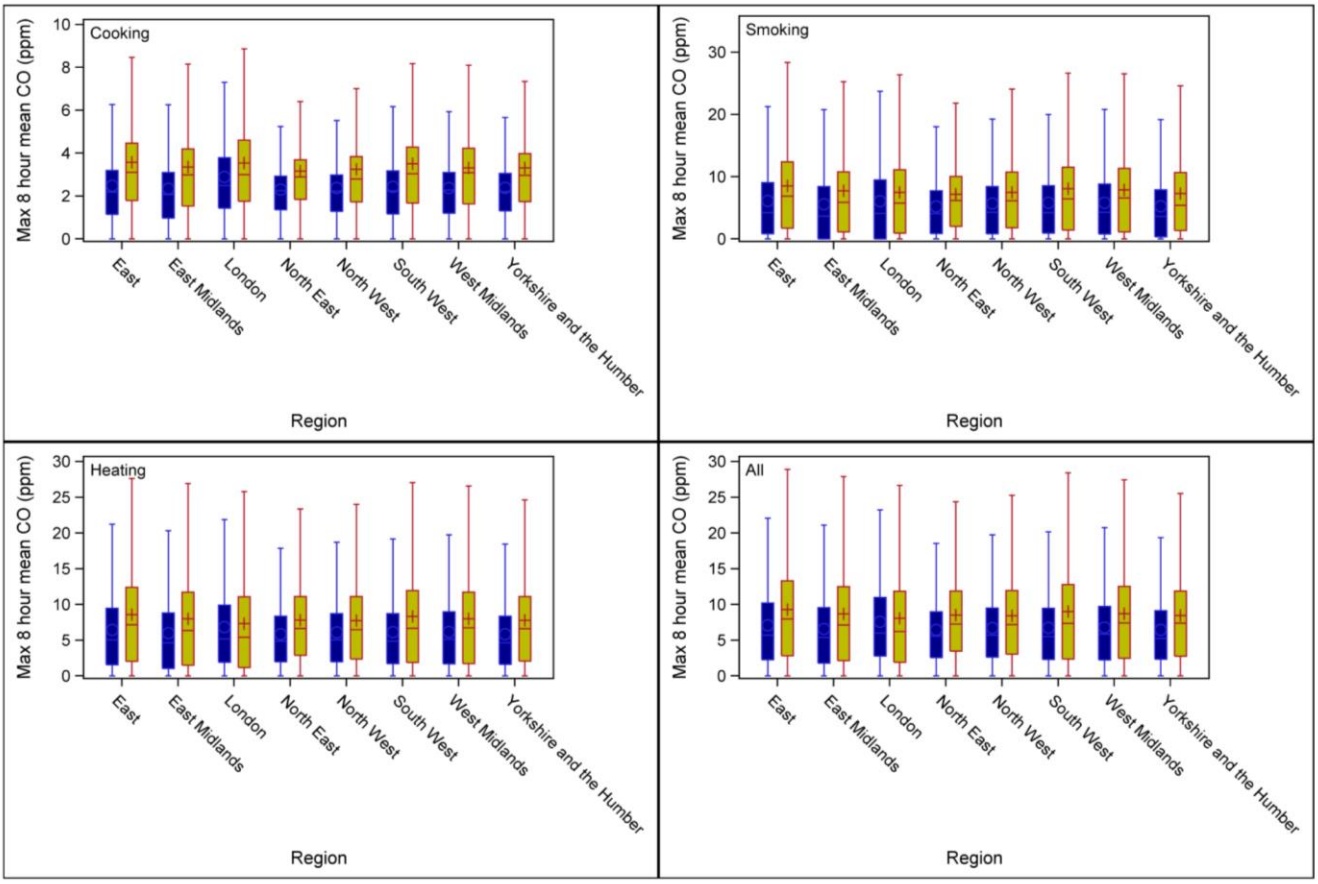

Figure 14 The annual maximum of the 8-hour rolling mean CO concentration (ppm) by dwelling variant for cooking (kitchen), smoking (living room), heating (living room), and all sources (living room) by region. Blue is modelled under current building stock conditions, while Yellow represents a full retrofit.

4.2.2 EPC

The results of the application of the metamodel to the EPC dataset can be seen in Figures 15-17, showing the spatial variation in housing modification of potential CO exposure. For cooking, trends are evident in locations with smaller kitchen floor areas, including urban areas, and in particular London. Due to the lack of information on cooking appliances, all models are run assuming a gas cooker is used alongside an extract fan. Many dwellings in urban areas – such as high-rise flats – may not have mains gas connectivity, and so will cook using electricity. For smoking (Figure 16), elevated levels can also be seen in constituencies with generally smaller floor areas. However, in contrast to cooking, no additional ventilation is provided during smoking activities, meaning that dwelling characteristics, including permeability, and local wind exposure have a greater impact on the spatial trends in indoor CO levels from smoking. For heating systems, similar trends can be seen (Figure 17), with the added effect of the types of fuels used for heating for the dwellings in each constituency.

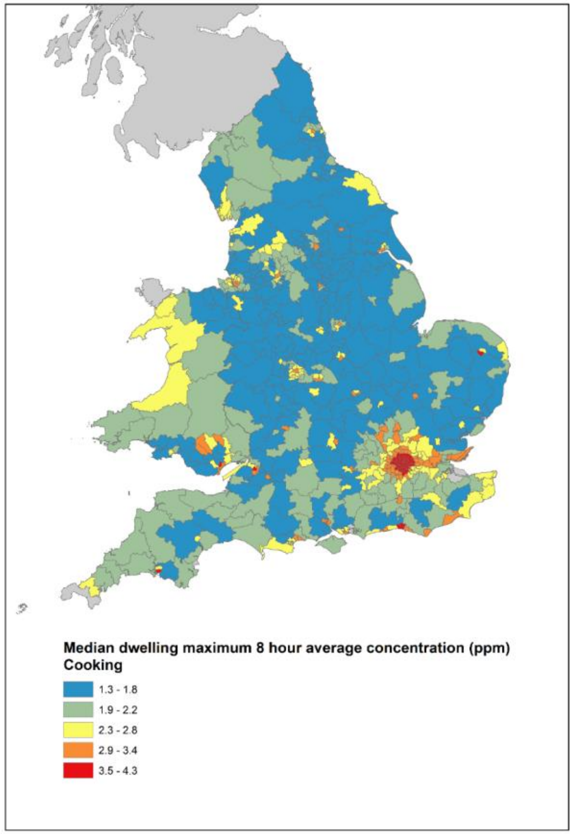

Figure 15 The median annual maximum of the 8-hour rolling mean CO concentration (ppm) from **cooking (kitchen)**, for dwelling in each constituency in England and Wales, modelled from EPC data.

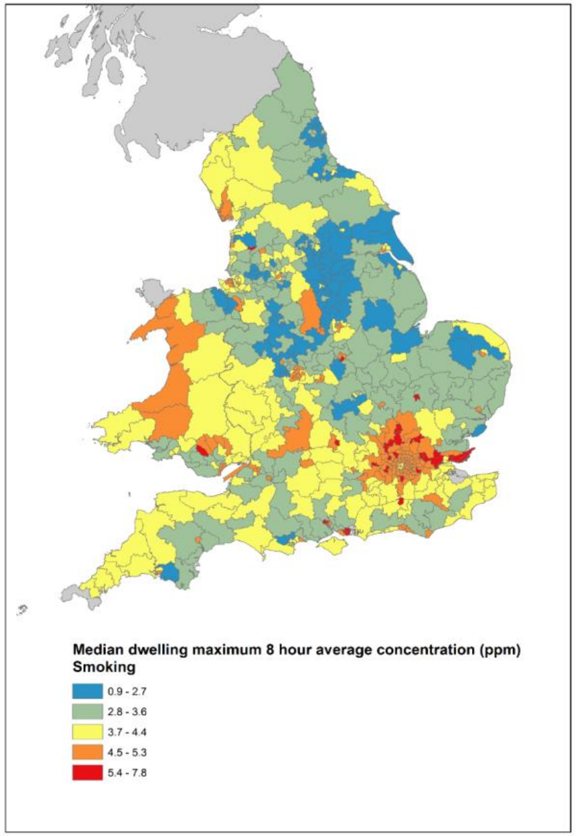

Figure 16 The median annual maximum of the 8-hour rolling mean CO concentration (ppm) from **smoking (living room)**, for dwelling in each constituency in England and Wales, modelled from EPC data.

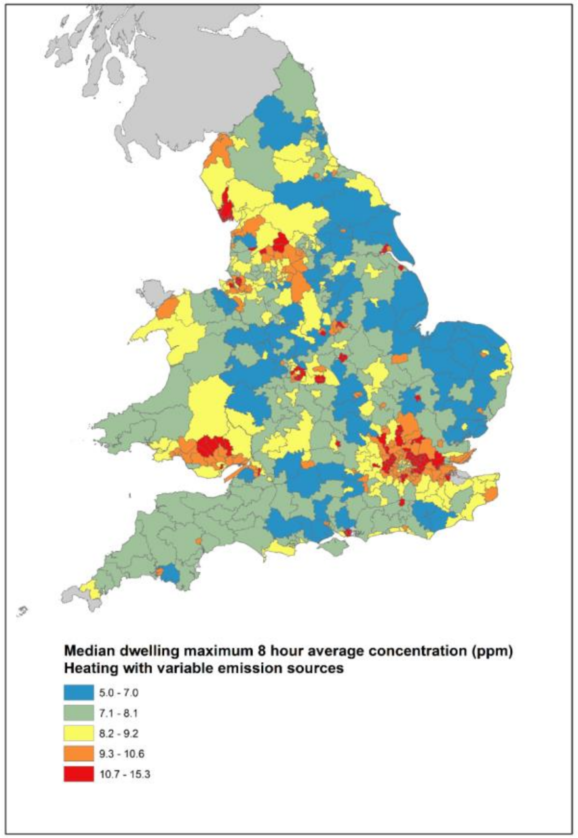

Figure 17 The median annual maximum of the 8-hour rolling mean CO concentration (ppm) from **heating systems (living room)**, for dwelling in each constituency in England and Wales, modelled from EPC data.

The overall maximum 8-hour mean CO concentration across England and Wales, including the background concentrations, can be seen in Figure 18. This represents the sum of the annual maximum of the 8-hour mean indoor and outdoor concentrations - a theoretical maximum exposure. In general, indoor sources contribute a greater risk to background CO exposure than outdoor sources, and levels are estimated to be highest in urban areas due to the higher background levels and smaller dwellings in which CO emitting activities take place. Retrofits will increase the overall CO exposure risk in dwellings (Figure 19), particularly in urban areas. Under current conditions, it is estimated that 37.8% of the housing stock in England will exceed the EU limit for 8-hour average CO levels (8.11ppm), while after the wholescale retrofit of the stock this is estimated to increase to 51.7%. The spatial variation in this change can be seen in Figure 20, demonstrating the increase in risk in urban areas relative to rural areas.

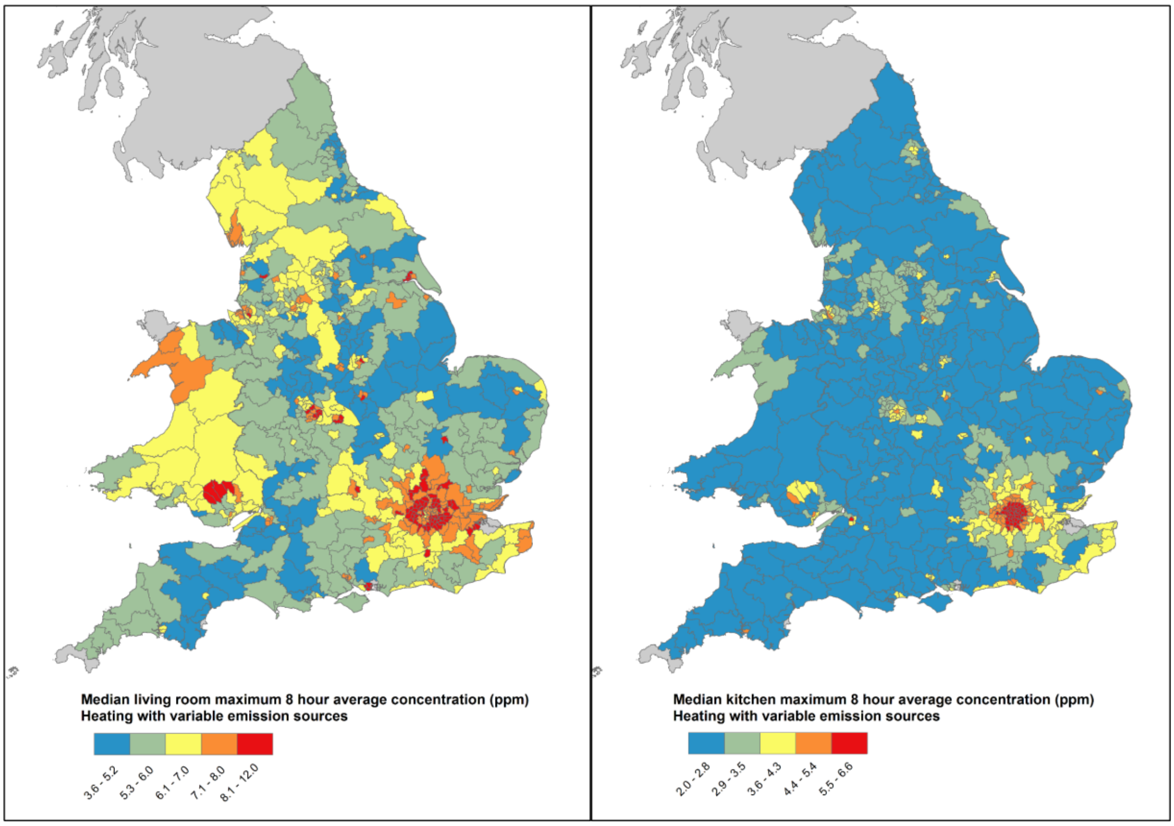

Figure 18 The median annual maximum of the 8-hour rolling mean CO concentration (ppm) from all sources plus the annual maximum 8-hour mean outdoor concentration for dwellings in each constituency in England and Wales, for living rooms (left) and kitchens (right).

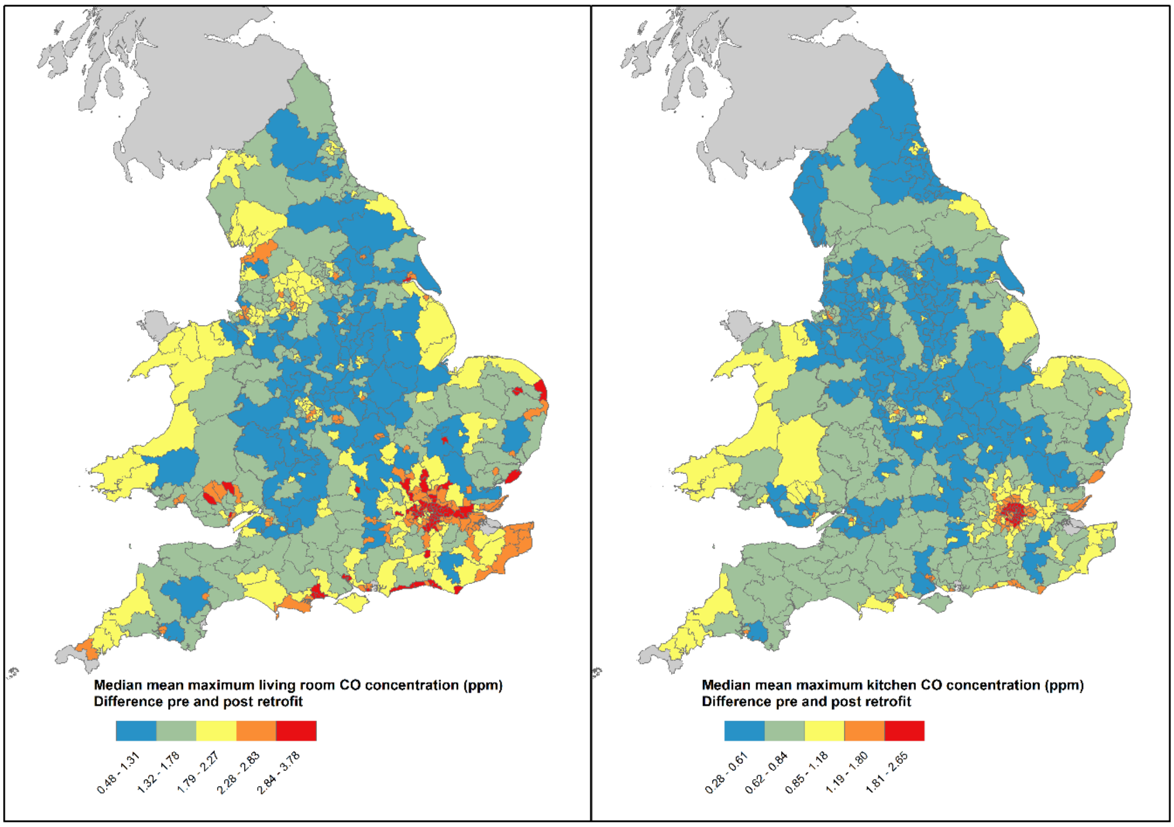

Figure 19 The median increase in annual maximum of the 8-hour rolling mean CO concentration (ppm) from all sources post retrofit for dwellings in each constituency in England and Wales, for living rooms (left) and kitchens (right).

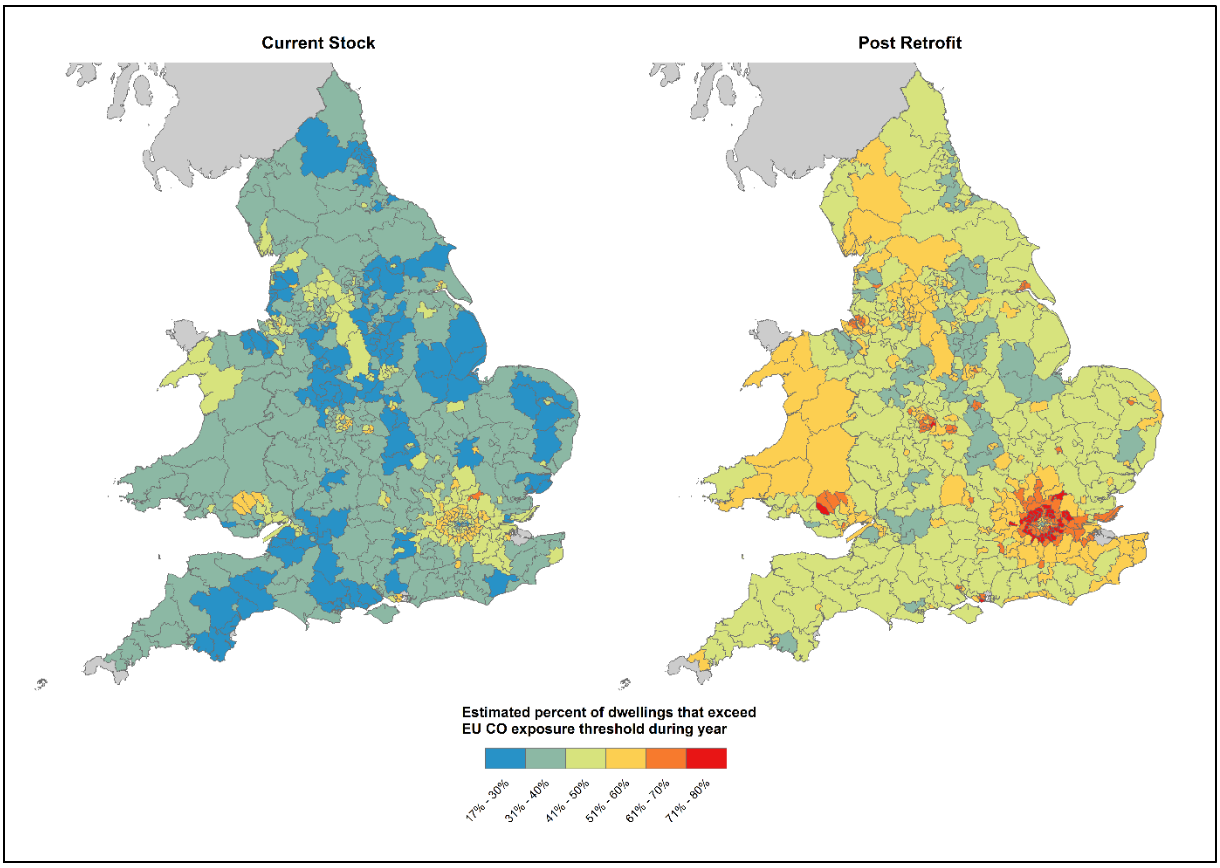

Figure 20 The percent of dwellings in each constituency that exceed the recommended EU limit of 8.11ppm under current stock conditions (left) and following the retrofit scenario (right) for both indoor and outdoor sources.

5. DISCUSSION

The analysis of the EHS dataset demonstrates the differences in primary fuel use across the stock, which also indicates the presence of a risk factor for CO risk exposure. The variation in fuel across dwelling types was one of the primary reasons variations were seen across different tenures and regions, as the fossil-fuel burning systems were less prevalent in low-rise and high-rise purpose-built flats due to building regulations. There was little variation across the stock – by dwelling age, type, tenure, or region – in the surveyors' subjective opinion of CO risk, whether due to the conditions of the boiler, or the HHSRS rating. This may be due to the relatively small sample size in the EHS, as well as biases within the EHS surveyors – for example there were significantly fewer dwellings with perceived 'higher than average risk' than there were with 'lower than average risk', when one would expect similar levels. It is suggested that one possible reason for this may be the guidance given on CO within the HHSRS.

The analysis of the EPC dataset also reflects the variation across dwelling type due to the different heating systems in place. The geographical variation in housing and heating fuels meant that fuel use could be mapped across England and Wales, identifying locations where potential CO-producing fuels are used. Urban areas had higher levels of mains gas connectivity (and in the case of London, greater access to community heat), while solid fuels were more common in rural areas. While this work has examined the use of heating fuels across the English and Welsh housing stocks, and through the review of the scientific literature found emission rates for different heating systems, there is limited information available on which types of heating systems are more prone to producing CO indoors, and so these analyses are largely exploratory. From this work, an estimated 37.8% of houses in England and Wales would exceed the WHO threshold at some point during the year. This equates to around 9 million dwellings in England – much higher than the estimated 100,000 dwellings at risk of CO levels reaching levels high enough to cause negative health effects, as estimated by Croxford (2008). This is likely due to a number of reasons, including the inclusion of smoking and gas cooking in all housing in the modelling work described here (as this is considering the worst case scenario), as well as using different metrics of exposure.

The application of the metamodel to the housing stocks produced estimates for both the EHS and EPC datasets. For the EHS, the indoor concentrations were dependent on the CO emission rates, the volume of the room where the activity was taking place, and the rate of removal of the contaminated air. The removal of CO-contaminated air is dependent on both the background ventilation of the dwellings – due to the permeability of the external building fabric, the number of sides of the building exposure, and the effect of the surrounding terrain on wind exposure – as well as any PPV used during the CO-producing activities. For cooking, dwellings with smaller kitchens – or those without functioning extract fans –

experienced higher CO concentrations. This included bungalows, converted flats, and low rise purpose-built flats. For cooking, it was assumed that gas stoves were used in all dwellings due to a lack of information on cooking fuels; this is clearly not the case in reality, but this assumption enables the relative differences in exposure due to housing construction and design to be examined. For smoking, no additional PPV was provided, and indoor concentrations were dependent purely on building characteristics. Here, dwellings with limited ventilation rates also experienced the greatest concentrations, including bungalows, low rise flats, mid terraced dwellings, and semi-detached dwellings. Heating systems included variable emission rates based on data from the literature, and identified properties with smaller living rooms that used solid fuels as being those with an elevated risk of CO exposure. The combination of all CO sources indicated that many bungalows, converted flats, and mid terraced buildings are at risk of exceeding the EU limits on CO exposure, and that retrofits are likely to increase this risk where PPV is not included as part of the scheme. The mapping of the results of the EPC model runs reflects the spatial variation in housing stock and fuel use. When combined with background levels from outdoors, London was identified as being a location of elevated CO exposure risk.

5.1 Research Limitations

There are number of limitations to the above research, which are discussed in this section.

5.1.1 Building Stock Data

Both the EHS and EPC data has been collected by trained surveyors, but for different purposes. In the EHS, an in-depth survey of dwellings is carried out for a subsample of dwellings, and a number of building characteristics are recorded. Nonetheless, discrepancies may be found, particularly with subjective reporting of risks within the HHSRS component of the survey. Errors or biases by the EHS surveyors are likely to be present in the data, with implications in the analysis. Additionally, while the EHS is designed to be statistically representative, extreme risk for CO exposure is likely to be very limited across the stock, and may not occur at significant levels with the EHS sample.

The EPC dataset is also collected by trained surveyors for energy performance assessment, but has a limited amount of building information when compared to the EHS. There are a greater number of inconsistencies in the EPC dataset than the EHS, which are being explored in ongoing work. These inconsistencies include missing data, or free text fields with different methods of describing building characteristics. Nonetheless, the EPC remains one of the largest datasets with domestic property information available in the UK, and the only means of evaluating the spatial variation in dwelling variants and heating fuels. In both the EHS and the EPC, there is no data to inform the fuels used for cooking, while the EPC lacks data on extract fans.

5.1.2 Limitations of Multizonal Models

The metamodel performance results for the various built forms show a high degree of accuracy has been achieved in testing. However, there are a number of limitations to the underlying multizonal models which are acknowledged here. Some are due to the nature of the model construction and necessary assumptions, whilst other are due to the scope of the project. This section looks at these briefly and offers some potential solutions:

Each building modelled within EnergyPlus was created as a series of nodes which represent zones with airflow elements such as cracks, windows, doors and ducts. The resulting simultaneous non-linear equations determine the flow through the building with the ability to model whole building infiltration and ventilation rates. By using this network model, transient weather files with variable wind speed and direction were employed to generate more realistic scenarios than those achieved with fixed values. In addition, buoyancy and stack-effect impacts are included in the model due to the dynamic calculation of indoor temperatures based on external temperature profiles. It was then possible to predict consequent CO concentrations which were dispersed by these airflows. CO from internal sources are modelled in each zone, as well as the transport between zones. In addition, a range of purpose provided ventilation systems with various flow rates and other energy efficiency measures could be constructed. Time/event based schedules for activities within domestic properties and components give an indication of occupant behaviour influences. Post processing of results allows the effect of individual components/factors to be investigated.

However, as with all multizone models, there is an inbuilt assumption that the air along with any contaminant is uniformly mixed within each zone. This does not allow for any spatial variation within zones, and zonal concentrations reflect the ‘average’ within the room. In reality, any individual close to a pollutant source may be exposed to a higher concentration of the pollutant than an individual standing further away within the same zone. Complex fluid dynamics (CFD) could be used to investigate this, however, given the complexities of applying these to a large number of buildings in the modelled building stock and the additional computer processing required, these have not been used in this study.

As well as to proximity to the source, movement of occupants within the home can greatly influence potential exposure. For example, in the case of $PM_{2.5}$, an airborne pollutant with known health impacts, Shrubsole et al. (2012) found that peak exposures occurred during cooking in the kitchen, with cooks exposed to twice the concentrations of airborne pollution compared to the average household concentration and over four times the exposure experienced by those who do not enter the kitchen during cooking events. Investigation of occupant movement within the property, for example by varying occupant schedules, will help to understand the range of exposure profiles present in dwellings. Additionally, post-processing of the zone concentrations and creation of additional metamodels may quantify exposures for different occupants.

5.1.3 Model Input Assumptions

This project and its modelling is dependent on the quality and range of input variables available. Where empirical data is not available such as in the case of occupancy patterns, these are based on assumed behaviour. Occupancy in the model is based upon a retired couple who spend all of their time at home. This scenario was chosen in order to highlight the upper-bound case in terms of indoor CO exposure, and to enable the comparison of housing modification of CO exposure risk rather than combined housing and behavioural effects. However, there are numerous other occupancy patterns and behaviours, including many where the occupants (more or less in number) would only be present in the dwelling for part of the time. For studies that investigate population-level distribution of CO exposures, a wider range of occupant behaviours need to be considered. Similarly, it was assumed that smokers and gas cookers were present in every house modelled in order to demonstrate the relative role of housing on CO exposure. Emissions from specific sources could be tailored in the future to specific dwellings should more data become available.

Apart from movement and occupancy patterns, occupant behaviour in terms of window opening and ventilation behaviour will have a dramatic impact on the concentrations of CO in homes. A clearer understanding of such behaviour could be achieved by the use of the Energy Follow Up Survey (BRE, 2013) data set. This data could be used to inform the range of heating and potential window opening behaviour. The metamodel is capable of modelling a range of window-opening behaviours relative to indoor temperature thresholds, and can be used to further analyse model sensitivity to these assumptions. Whilst future scenarios incorporate airtightening and some compensatory ventilation, full systems such as mechanical ventilation and heat recovery (MVHR) systems have not been modelled. In air-tightened buildings in the future scenario, these would increase air change rates by boosting ventilation thereby reducing indoor CO concentrations. Future work could look at the stock fitted with MVHR or similar systems.

Some parameters in the model are static. The internal layout of a home can have significant impact on the concentrations of CO within buildings. Whilst the model can adapt to reflect variation in dwelling floor areas by shrinking or expanding the building, it is not able to change the floorplan of the dwellings. This has important considerations for contaminant airflow in dwellings – for example, the CO concentration will be higher in a living room directly adjoining a kitchen when cooking, than it would be if the living room were located down a hall. The floorplans of the modelled building have been developed using data from the English Housing Survey to represent the 'average' building for each built form in the English housing stock, but is unable to account for individual variations in this floorplan. Further research should investigate the sensitivity of the model outputs to such variations.

The most significant limitation of the study is the emission rates from different activities. There is little data available on the emissions from different sources, particularly from different heating fuels in the UK. Emission rates from heating were modelled assuming 90% of sources were vented outdoors, which resulted in indoor concentrations for gas appliances similar to those found in other studies (Traynor et al. 1989) as well as values referenced in the literature review. However, the variation in emission rates by fuel types are from a range of studies internationally, and there is little data to support such variations in the UK housing stock. Furthermore, in the majority of field studies, it is not possible to separate the indoor concentration from indoor sources from the indoor concentration from outdoor sources due to a lack of concurrent outdoor measurements. Further research is required to identify CO emission rates for UK appliances that may be incorporated into Multizonal models such as EnergyPlus. As such, the strength of the presented results lie in the relative concentrations across housing variants rather than absolute concentrations.

5.2 Future Work

This project represents the first implementation of an indoor air quality metamodel to housing in the England and Wales. Further work will develop the model to simulated additional pollutants, such as $PM_{2.5}$ and radon, in order to understand the variation in indoor exposure to air pollution across the English housing stock, and to estimate the potential impacts of energy efficient retrofits on population health. Ongoing calibration of the model will occur when more empirical emissions and indoor concentration data becomes available.

6. CONCLUSIONS

This report has examined the variations in risk of low-level but potentially harmful CO exposure across the English and Welsh housing stock using available housing stock databases, and by developing and implementing a metamodel to estimate indoor concentrations across the stock. Results indicate a wide range of relative risks across the housing stock, with certain dwelling types such as converted flats, at greater risk than others. Retrofitting is expected to significantly increase the number of dwellings that exceed the EU limits of CO exposure during a year by around 15% where PPV is not explicitly included as part of the refurbishment scheme. Further research is required to obtain empirical data on indoor CO emissions and indoor concentration ranges from different indoor appliances.

7. ACKNOWLEDGEMENTS

This report is based on work carried out between the September 2016 and August 2017 at University College London. It was funded by the Gas Safety Trust (GST); whose support the authors gratefully acknowledge. The team also wishes to acknowledge the help, guidance and insight given by the advisory team.

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9. APPENDICIES

Appendix A. Literature Review: Key Words used for Investigation

Initial Keywords	Combination Words
CO, Carbon monoxide, CO emission/s, CO source/s, CO concentration/s, CO exposure/levels, CO low-level exposure, CO measurement, CO monitoring, CO monitoring equipment, Carboxyhaemoglobin/COHb.	Indoor, Health, Housing, Domestic, English Housing, Cooker, Gas cooker, Smoking, Gas fire, Leakage/Leaks, Morbidity, Policy, Regulations.

Appendix B. Dwelling Archetypes

Figure B1. Dwelling archetypes for end terrace, mid terrace, semi-detached, and detached dwellings.

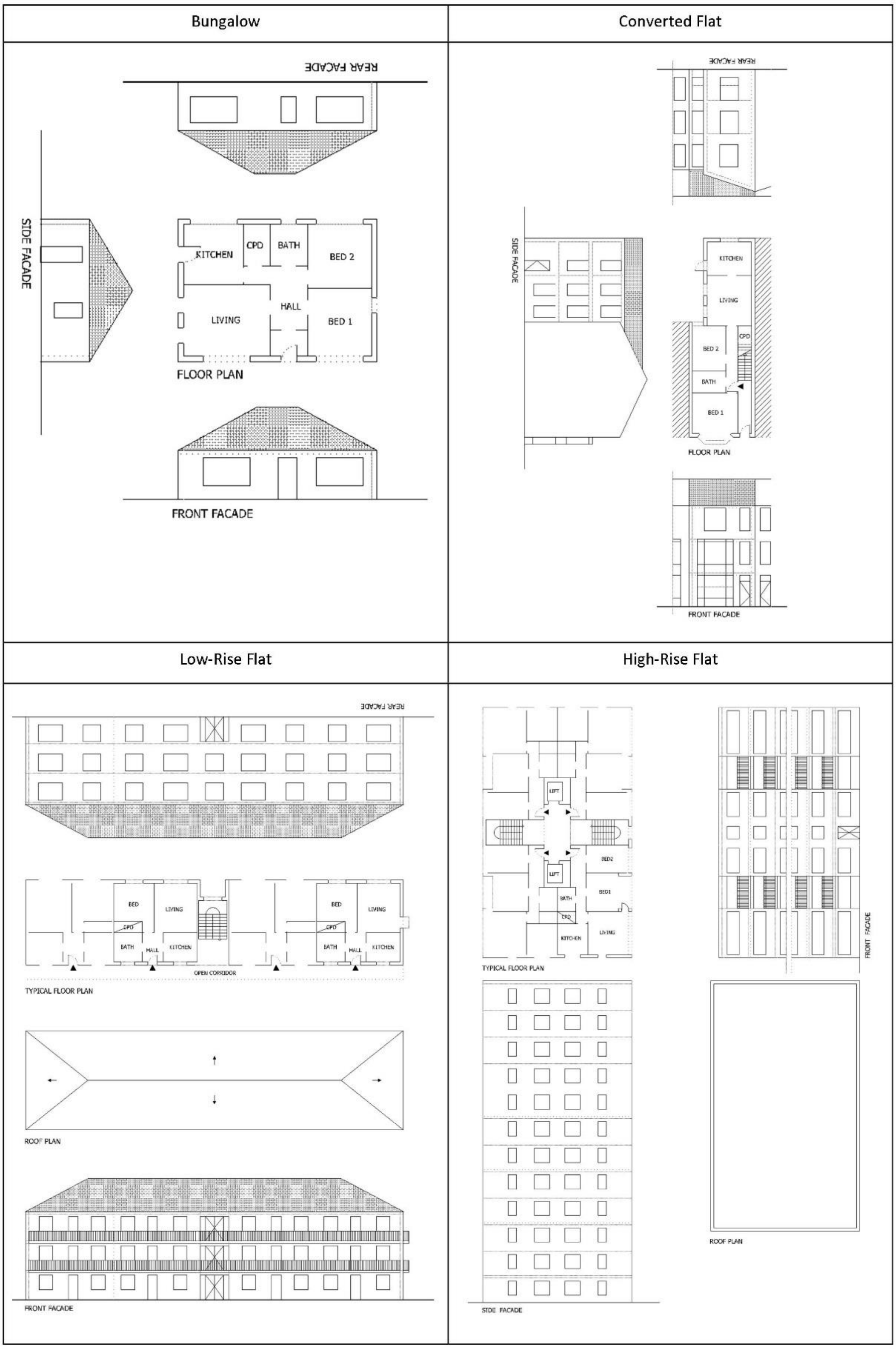

Figure B2. Dwelling archetypes for bungalows, converted flats, low-rise flats, and high-rise flats

Appendix C. EPC Data – Postcode Maps

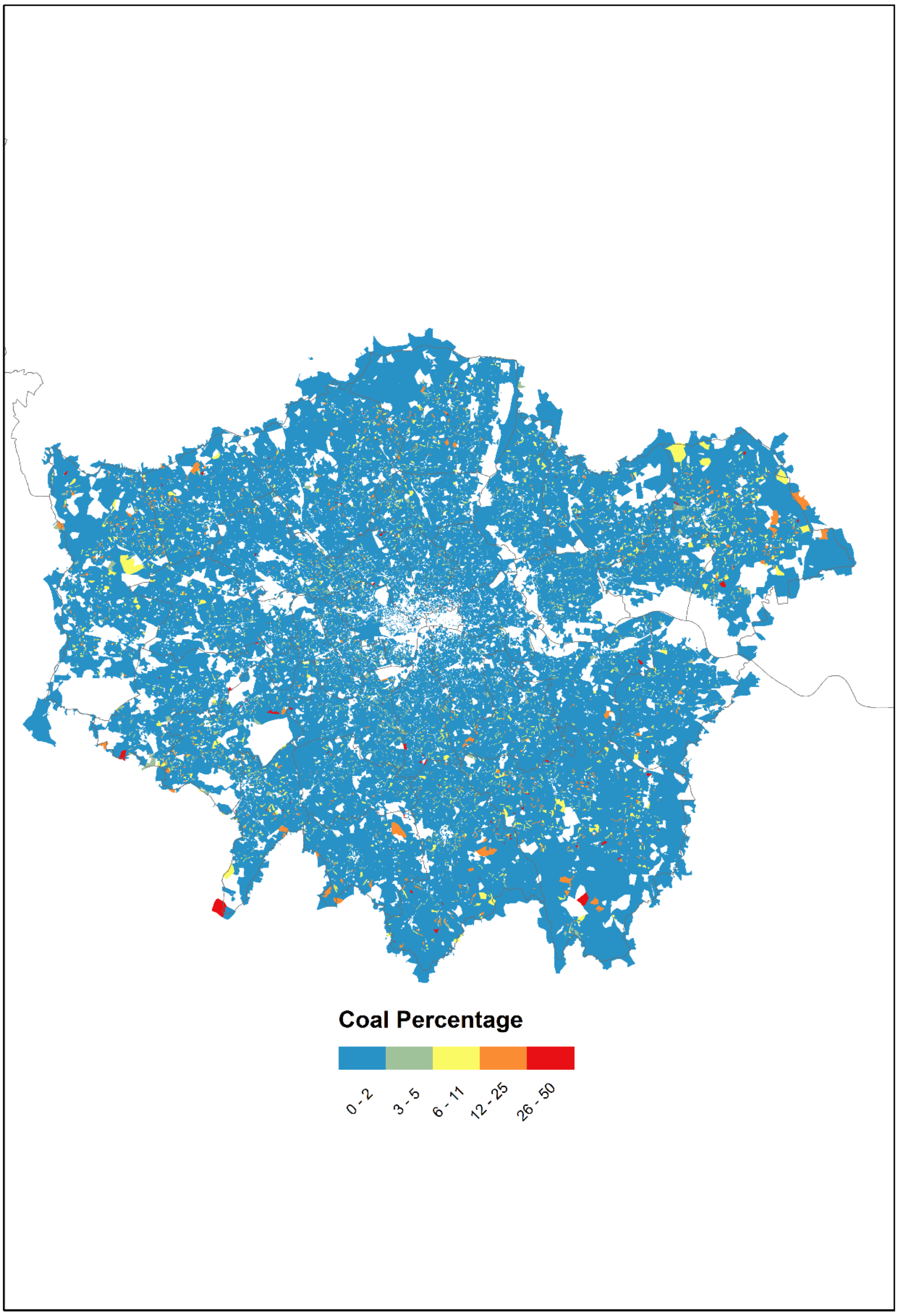

Figure C1. The percent of dwellings with coal as the primary heating fuel in each constituency, according to EPC data.

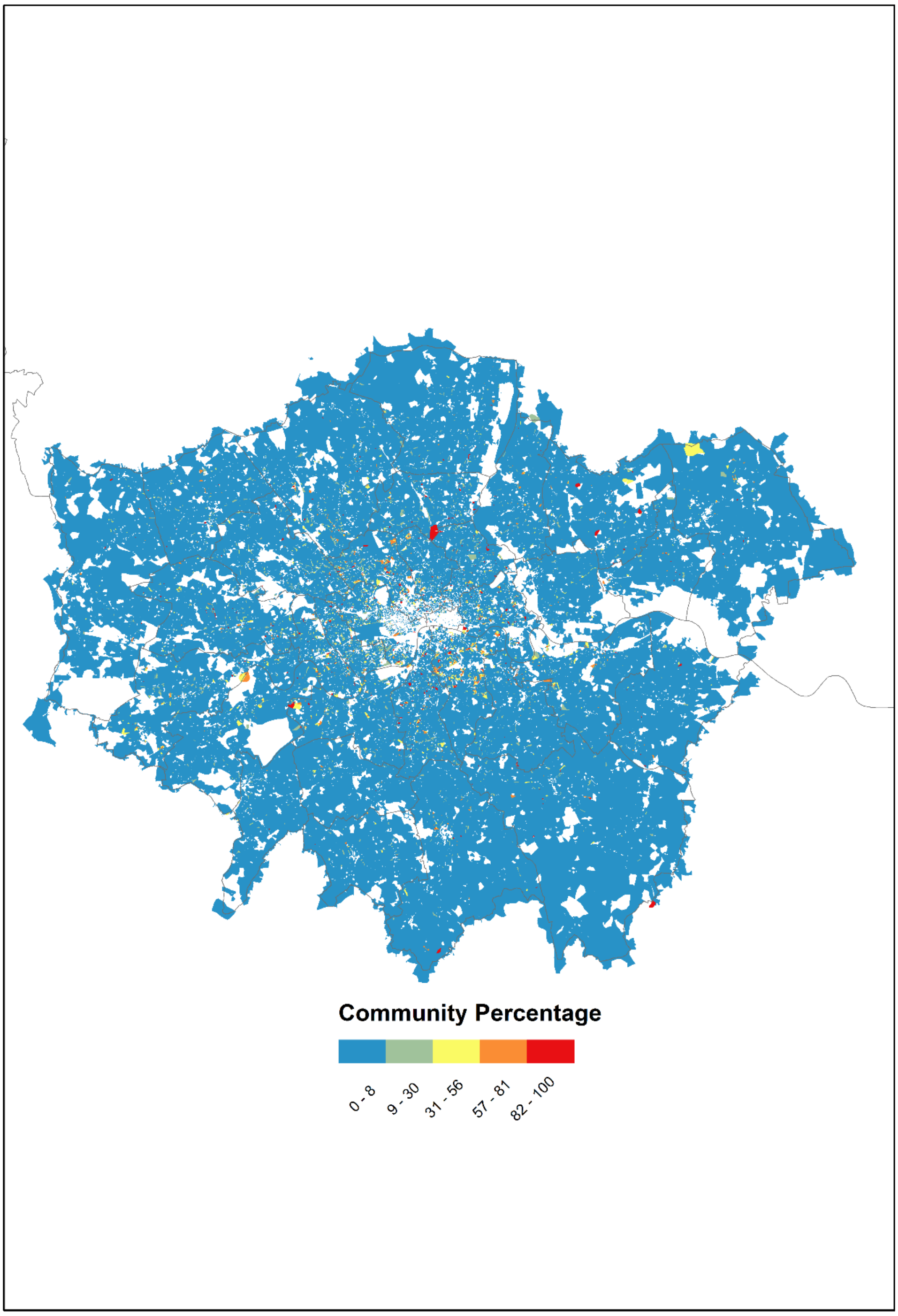

Figure C2. The percent of dwellings with community heat for heating in each constituency, according to EPC data.

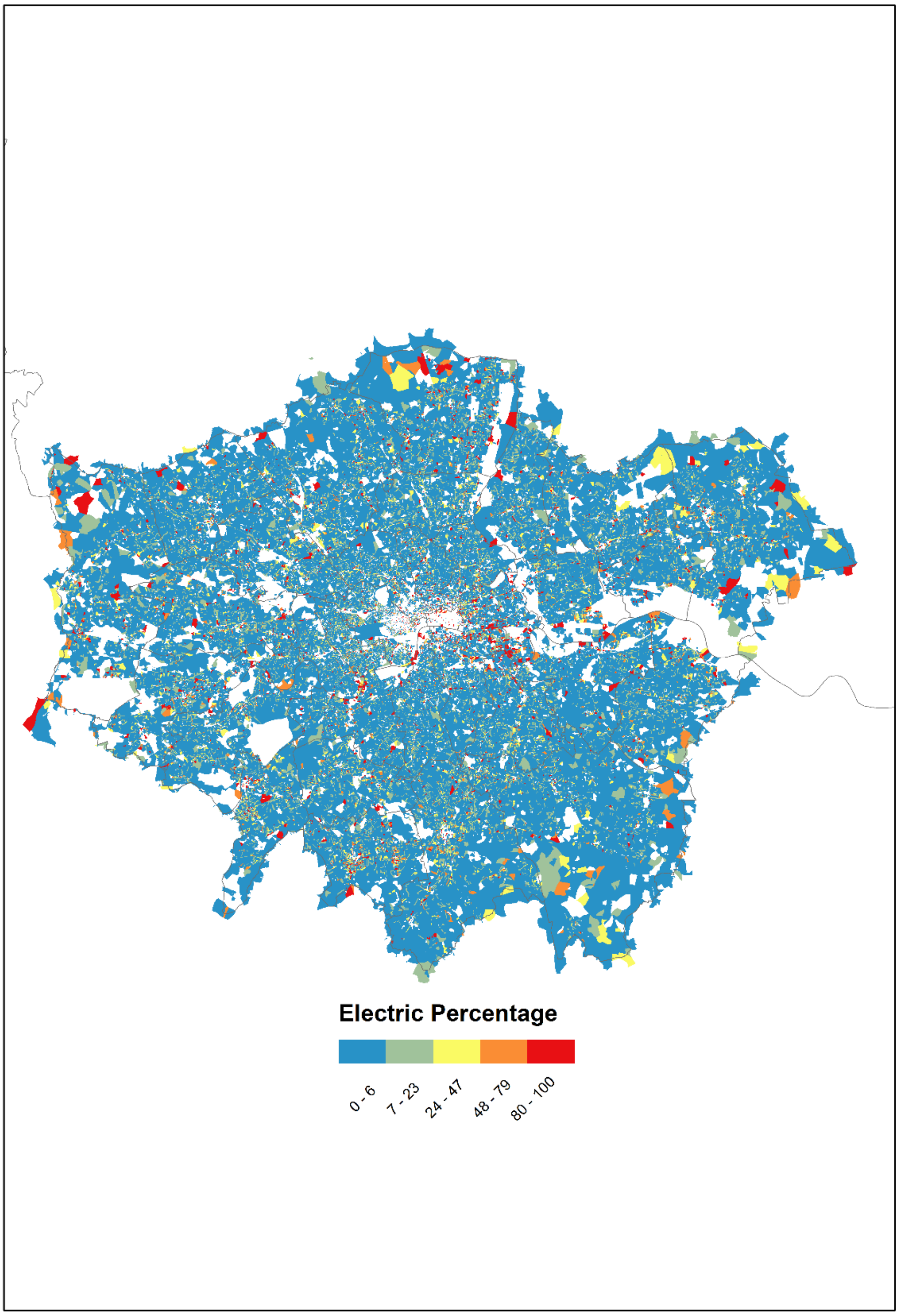

Figure C3. The percent of dwellings with electricity as the primary heating source in each constituency, according to EPC data.

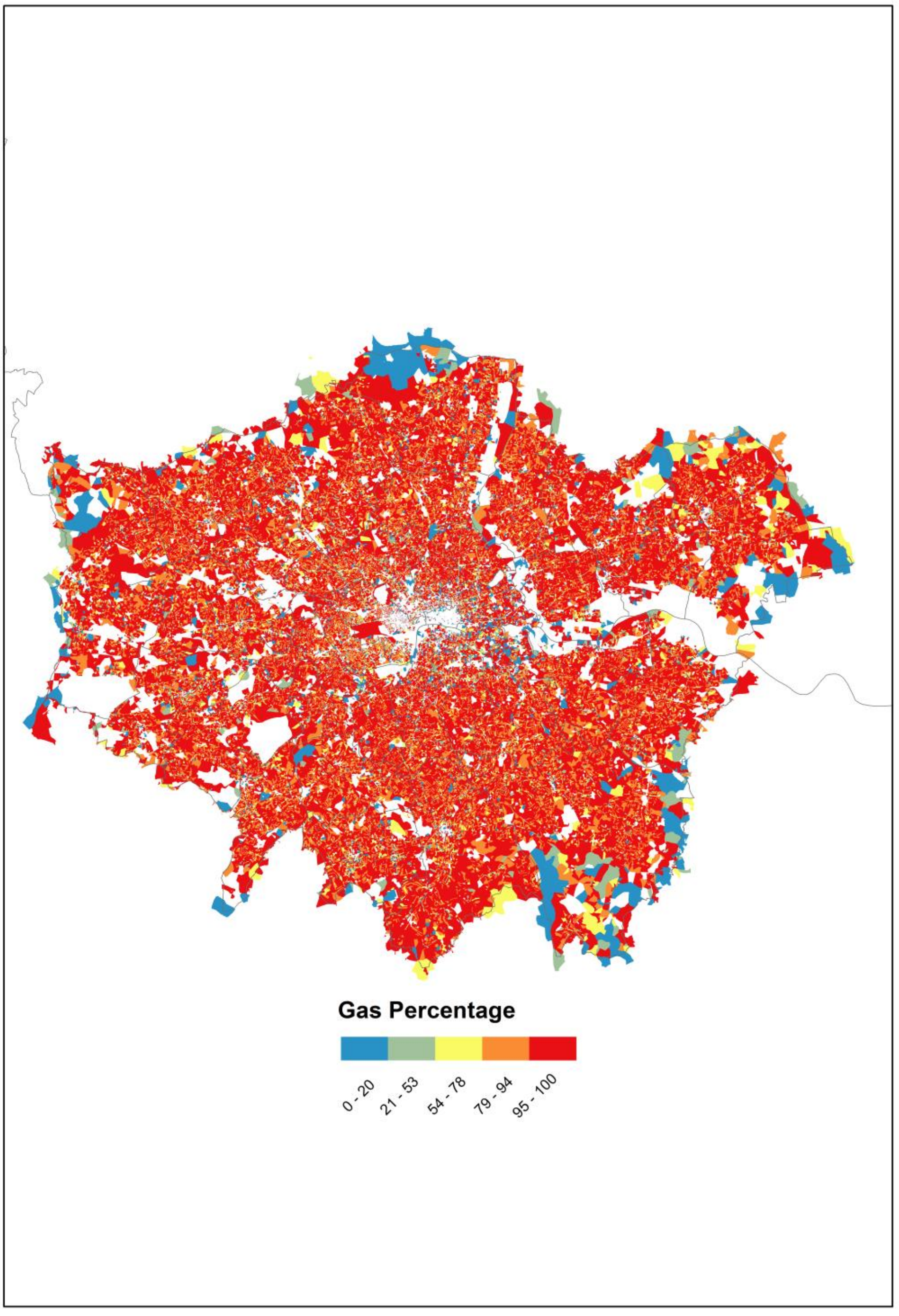

Figure C4. The percent of dwellings with mains gas as the primary heating fuel in each constituency, according to EPC data.

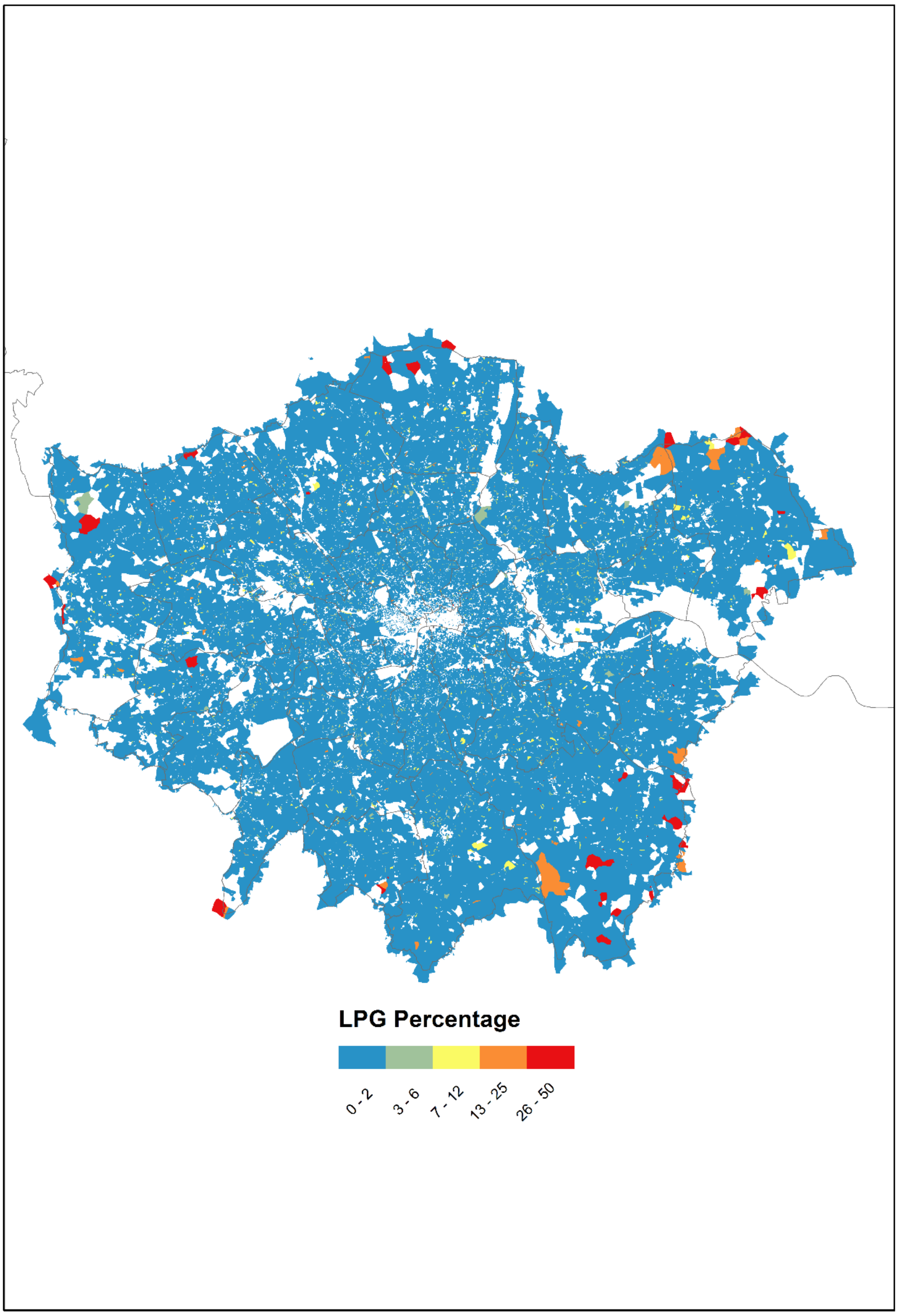

Figure C5. The percent of dwellings with LPG as the primary heating fuel in each constituency, according to EPC data.

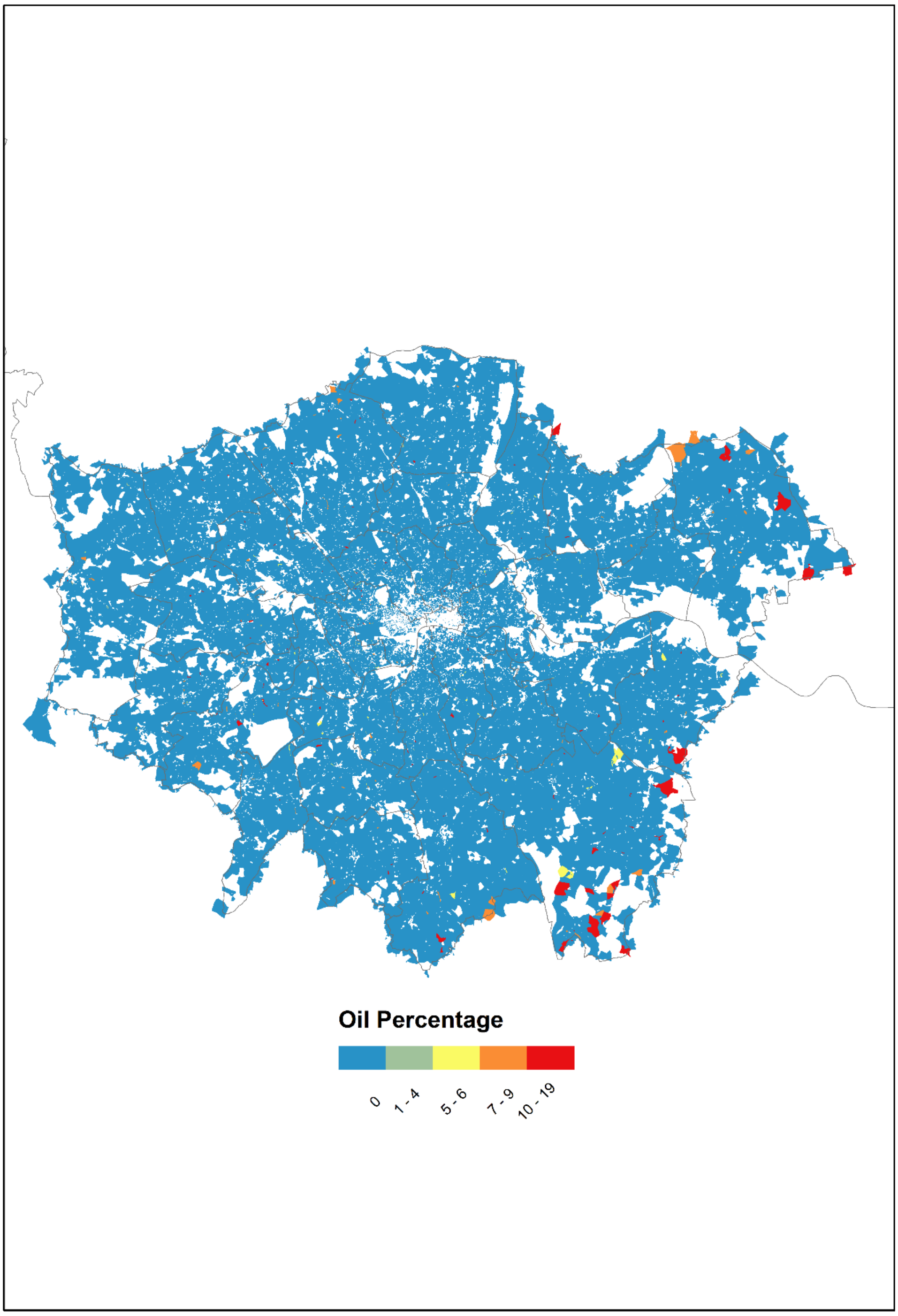

Figure C6. The percent of dwellings with oil as the primary heating fuel in each constituency, according to EPC data.

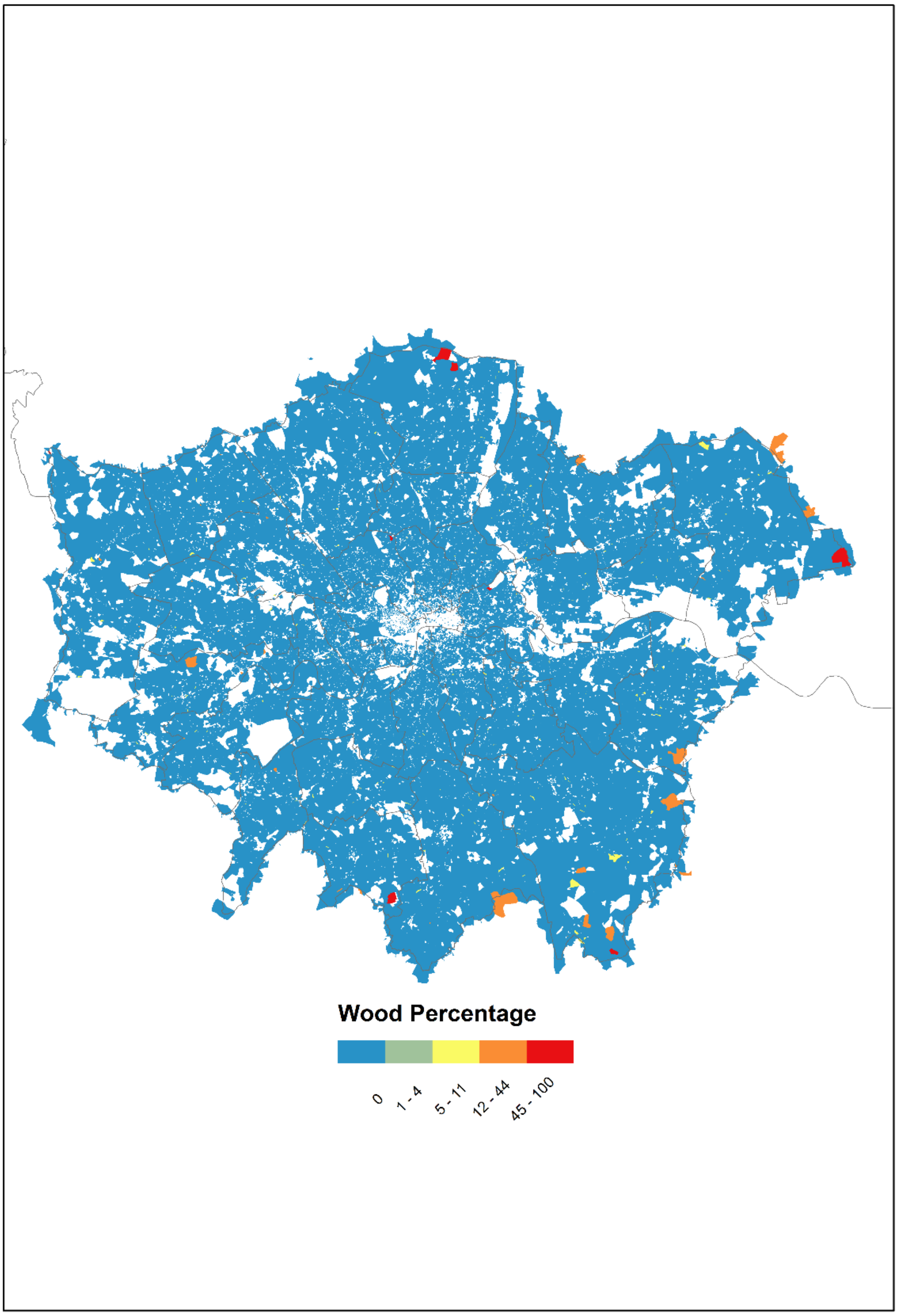

Figure C7. The percent of dwellings with wood as the primary heating fuel in each constituency, according to EPC data.

Appendix D. ICUH Conference Abstract

Abstract accepted for the 14th International Conference on Urban Health (ICUH): Health Equity: The New Urban Agenda and Sustainable Development Goals

Title:

Factors contributing to low-level carbon monoxide exposure in the English housing stock

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Phil Symonds UCL Institute for Environmental Design and Engineering, University College London

Jonathon Taylor UCL Institute for Environmental Design and Engineering, University College London

Mike Davies UCL Institute for Environmental Design and Engineering, University College London

Introduction:

The proportion of homes with a low-level risk of carbon monoxide (CO) exposure remains unclear. Reducing risk by addressing CO emission sources, such as poor gas appliance installation, may be achieved by regular servicing, awareness of the dangers of CO, and knowledge of how to use appliances correctly. However, the impacts of modifying factors on exposure, e.g. housing characteristics, location, occupant behaviours (including ventilation and CO-generating activities), and occupant demographics are uncertain. Consequently, there remains a major gap in knowledge about how best to identify the buildings and occupants at greatest risk and what measures are effective in providing protection.

Methods:

To determine and map the factors that lead to changes in CO exposure risk in English homes we used validated multizone indoor air quality and ventilation analysis modelling (EnergyPlus with its generic contaminant model) linked to the English Housing Survey (EHS), a representative sample of over 16,000 English dwellings. We modelled the current stock and a possible future stock subject to a variety of energy efficiency and ventilation interventions in line with carbon emission reduction goals. We investigated geographical factors, variations in window opening behaviour and between socio-economic groups and tenures.

Results:

Show that multiple factors can increase CO exposure including: ventilation behaviour (with the highest exposure in the winter months) and dwelling geometries. Energy efficiency measures when not combined with purpose provided ventilation (PPV) result in greater levels of CO exposure due to reduced air change rates. The use of extraction equipment especially during cooking, deceases temporary exposure spikes.

Discussion:

This is the first time low-level CO exposures and the impacts of building and occupant variables have been characterised in the whole English housing stock. Although further monitoring work is required, there are important messages for policy makers, gas suppliers and installers.

26-29 September 2017 Coimbra, Portugal. http://www.icuh2017.org/

Appendix E. ICUH Conference Presentation Slides

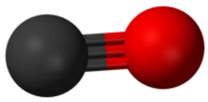
Factors contributing to low-level carbon monoxide exposure in the English housing stock

Clive Shrubsole, Phil Symonds, Jonathan Taylor

Institute of Environmental Design and Engineering, University College London, London, UK

International Conference on Urban Health 2017, Coimbra

Background



- Carbon Monoxide (CO) is a colourless, odourless gas known as a **'silent killer'**
- Produced through incomplete combustion due to **faulty gas appliances** (e.g. boilers & cookers)
- Poisoning is responsible for **200 hospital ad**missions and **50 deaths** per year in the UK (source: NHS)
- Regular **servicing** can prevent these type of occurrences
- Low level exposures to CO can lead to **food poisoning and flu** like symptoms
- **Building factors** and **external sources** may have a contributing factor to these low level exposures

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CO Exposure Scale (ppm)

10	WHO guideline max mean exposure over 8 hours
35	Headache and dizziness within six to eight hours of constant exposure
100	Slight headache in two to three hours
200	Slight headache within two to three hours; loss of judgment
400	Frontal headache within one to two hours
800	Dizziness, nausea, and convulsions within 45 min; insensible within 2 hours
1,600	Headache, increased heart rate, dizziness, and nausea within 20 min; death in less than 2 hours
3,200	Headache, dizziness and nausea in five to ten minutes. Death within 30 minutes
6,400	Headache and dizziness in one to two minutes. Convulsions, respiratory arrest, and death in less than 20 minutes
12,800	Unconsciousness after 2–3 breaths. Death in less than three minutes.

Sources: doi:10.1016/j.jen.2007.11.014 & doi:10.3122/jabfm.11.6.481

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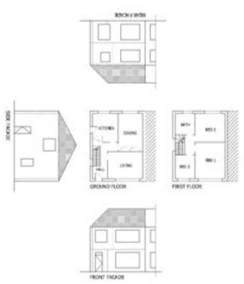
The English housing stock

- **22.8 million homes** in England
- **8** typical dwelling types
- **4** main occupancy types (tenures); owner occupied, private rented, local authority, housing association (RSL)
- Only **28%** have a CO alarm (mostly owner occupied)

Detached archetype

Semi-detached archetype



Terrace (end and mid)

Highrise, lowrise and converted flats

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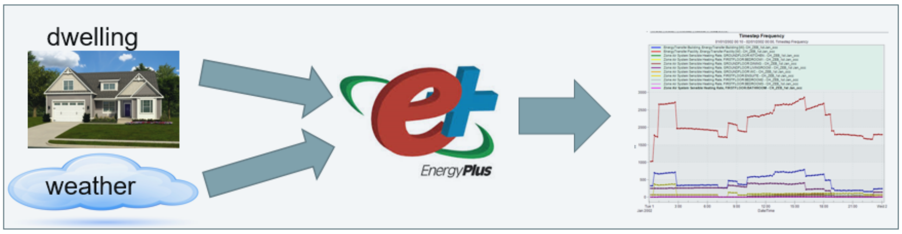
Methods

- A **dynamic thermal building simulation software**; EnergyPlus (US-DoE) is used to generate a metamodel for English homes



- **Nationally representative datasets** are then used as inputs to the model:

The English Housing Survey (EHS)
- Compiled every two years
- ~16,000 homes
- In depth info on dwelling and **occupant** characteristics
- Has fuel type, CO exposure risk, etc…

Energy Performance Certificates (EPC)
- Recently released dataset
- >18 million homes
- **Geographically locatable -> maps**
- No occupant info
- Has connectivity to mains (yes/no), main fuel type

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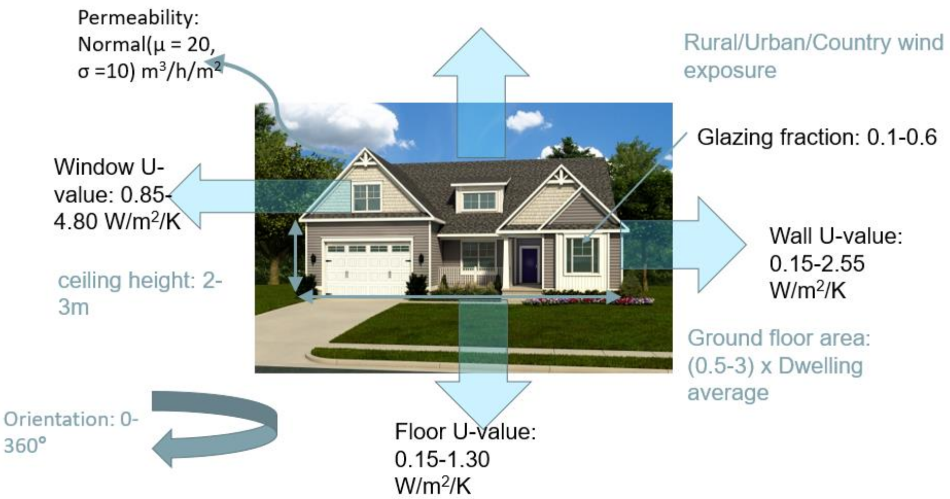
Methods – model inputs



Definitions:
U-values: Measure of heat transmission through building fabric elements (Conductive losses)
Permeability: Volumetric air infiltration rate per building surface area per hour @ 50pa (Convective losses)

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Methods

Model assumptions

- CO emission rates depend on the main fuel type used to heat/cook in the home
- **Heating** 16 hour/day in heating season (October-April)
- **Cooking** for 1.5 hours/day with emission rate of 1.0E-7 m3/s
- A **smoking** scenario is modelled with emission rate of 25-108 mg per cigarette smoked
- **Extract fans** can be present in the kitchen and bathroom. Active during cooking and bathing, respectively

Fuel/heating type	Estimated emission rate (m3/s)
Gas (mains)	2.2E-7
Bulk LPG or Bottled gas – propane	1.2E-7
Oil-fired	2.3E-8
House coal, Wood or Solids	4.0E-5
Community or electric	0

Sources:
10.1016/j.atmosenv.2008.07.019 &
10.1016/0004-6981(83)90253-6

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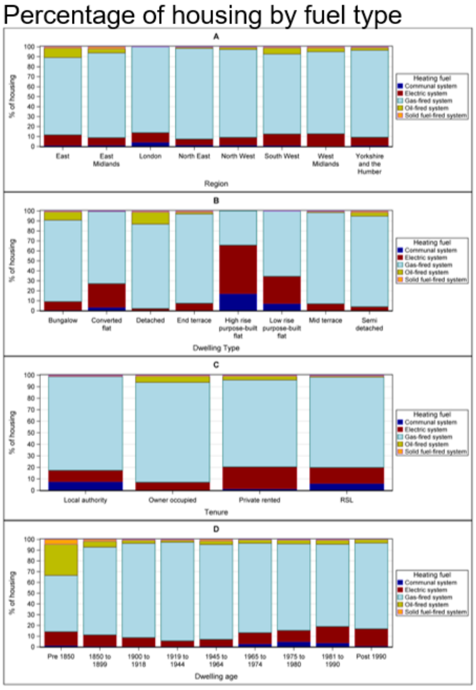
Results – EHS data

Percentage of housing by fuel type



- The majority of homes are heated by gas-fired systems
- Flats tend to use other fuel types (for safety reasons)
- Solid fuels still used in some older homes

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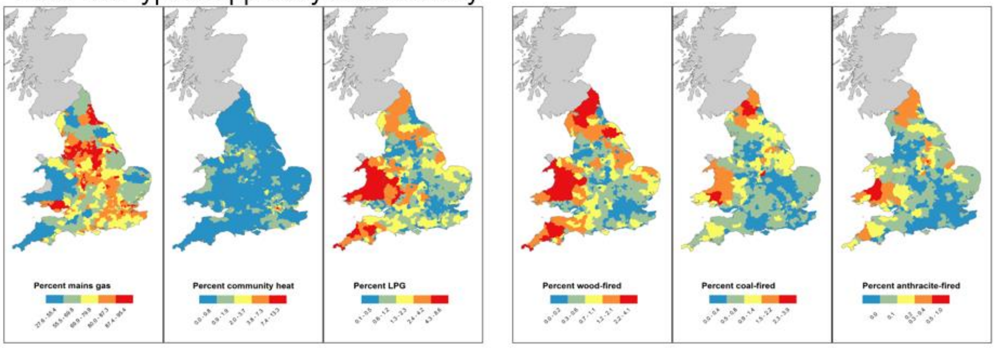
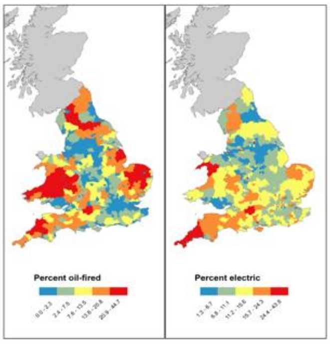
Results – EPC data

Main fuel type mapped by constituency





- Rural locations tend to have more solid, oil and electric fuel types
- Central London has the highest percentage of community heating

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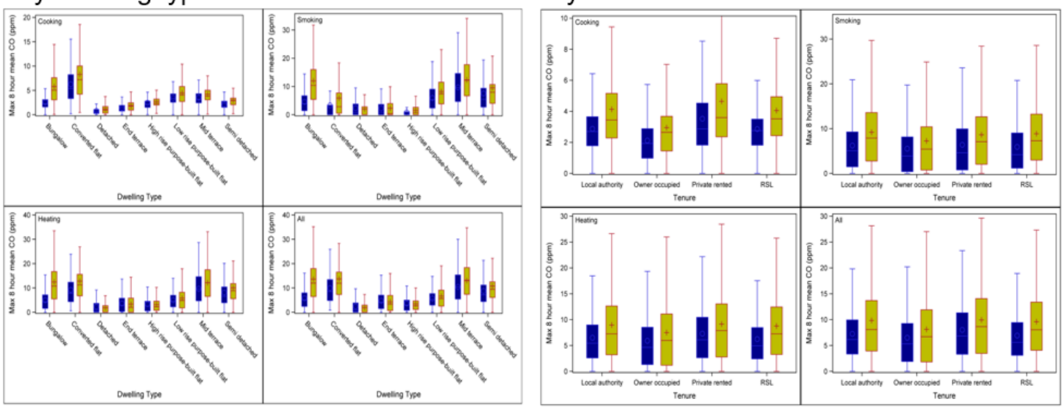
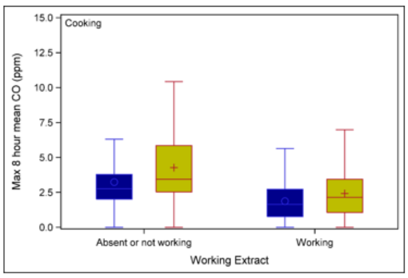
Results – Modelling (EHS)

By dwelling type

By tenure



With/without extract fans



- Flats tend to have higher CO exposures
- Own occupied dwellings have lower exposures
- Hiving working extract fans reduces exposures
- Energy efficiency retrofits increase exposures

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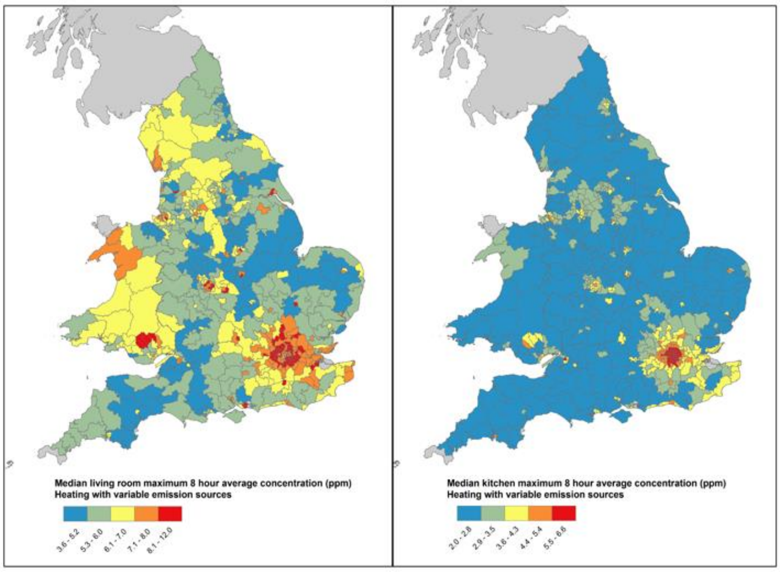
Results – Modelling (EPC)

All indoor and outdoor sources



- Cities, in particular London experience highest CO exposures
- A combination of small living spaces and high outdoor concentrations are to blame

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Summary

- Low level exposure to CO can cause nausea and headaches
- Dwelling type, main fuel type, floor area, how well ventilated a home is, and location act as modifiers to CO exposure
- Small flats in close proximity to busy roads are at particularly high risk
- Regular boiler services and the installation of a CO alarm could help prevent higher exposures

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UCL

Acknowledgement

- Many thanks to the Gas Safety Trust (GST) for funding this project

Gas Safety Trust

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