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BMJ Open
Health effects of home energy efficiency interventions in England: a modelling study

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ABSTRACT
Objective: To assess potential public health impacts of changes to indoor air quality and temperature due to energy efficiency retrofits in English dwellings to meet 2030 carbon reduction targets.

Design: Health impact modelling study.

Setting: England.

Participants: English household population.

Intervention: Three retrofit scenarios were modelled: (1) fabric and ventilation retrofits installed assuming building regulations are met; (2) as with scenario (1) but with additional ventilation for homes at risk of poor ventilation; (3) as with scenario (1) but with no additional ventilation to illustrate the potential risk of weak regulations and non-compliance.

Main outcome: Primary outcomes were changes in quality adjusted life years (QALYs) over 50 years due to improved efficiency interventions in housing.

Results: The modelling study estimates showed that scenario (1) resulted in positive effects on net mortality and morbidity of 2241 (95% credible intervals (CI) 2085 to 2397) QALYs per 10 000 persons over 50 years follow-up due to improved indoor pollutant exposures, highlighting the importance of ventilation to mitigate the risk of poor indoor air quality.

Strengths and limitations of this study

- The epidemiological evidence about health effects associated with indoor air pollutants and thermal stress is of varying certainty, though more evidence exists for exposure to outdoor pollution and temperature; therefore, only exposures with strong evidence were used.
- This study uses advanced validated building physics models to determine the change in indoor pollutant and thermal exposures related to energy efficiency retrofits.
- The uncertainty in the exposure responses on estimates of health impacts, such as the estimates for cold-related deaths, the toxicity level of particles derived from indoor sources and mental health, could result in a different balance of pollution impact depending on the assumptions made.
- While offering policymakers a support tool to include health as a criterion when developing and assessing home energy efficiency policy, the results presented here should be viewed with a clear understanding of the limitations associated with a modelling study.

INTRODUCTION

By 2030, the UK housing stock will undergo major changes to improve its energy performance,1 motivated by the need to reduce emissions of greenhouse gases (GHGs), considerations of energy security/cost, and concern about fuel poverty with its presumed link to the UK’s large burden of winter/cold-related mortality and morbidity.2 Housing is responsible for one-quarter of total UK CO2 emissions3 and 52% of this is from space heating. Meeting the UK’s ambitious energy efficiency targets will require investments to upgrade the energy performance of nearly all dwellings by 2030.1 These changes to housing energy performance will comprise one of the largest natural experiments in the indoor...
environment in the coming decades and these are likely to have major impacts on the indoor environment and population health. To date, health consequences have received limited examination, though they are increasingly being recognised as an issue by the UK Government. Properly designed and implemented, actions to improve housing energy performance could have major co-benefits for public health, although there are risks involved and the possibility of poorly designed interventions leading to unintended consequences (Figure 1). Energy efficiency retrofits that alter the fabric heat loss can also increase the air tightness of the dwelling, increasing exposure to indoor-generated pollutants (e.g., particulates, mould, radon). Living in cold or inefficient and poorly ventilated homes is linked to a range of health problems. Retrofits that improve indoor temperatures may have positive impacts on mental health and cardiorespiratory disease, but could have negative impacts on respiratory conditions due to the increased levels of indoor pollutants. In the UK, most of our time is spent indoors and the majority of the health impact of more airtight buildings is likely to occur over the long term through low-dose exposure.

While current English building regulations require that adequate means of ventilation is provided to dwellings, there is a lack of guidance for determining the level of ventilation required to protect health before or following an energy efficiency retrofit. The only guidance that exists relates to the replacement of existing window trickle vents. Ultimately, additional ventilation following a retrofit is left to the discretion of the installer or household. The aim of this study is to illustrate the potential health impact of energy efficiency retrofits under different ventilation settings.

In this paper, we describe the results of a modelling study to quantify changes in exposures in the indoor environment and their associated health consequences attributable to housing energy efficiency retrofits. We do this to characterise possible health-related consequences in need of further scrutiny for the development of national policies and guidance on housing energy efficiency interventions. By doing so, we attempt to gain a better understanding of the trade-offs between risks and benefits for population health.

METHODS

We developed a household-level model to quantify the principal exposure and health pathways outlined in Figure 1. The model comprised two parts:

1. A building physics model of English houses that quantifies indoor winter temperatures, exposures to particle pollution, secondhand tobacco smoke (STS), radon, mould growth and energy demand in relation to the energy performance of the dwelling; and
2. A model of the resulting health impacts based on a combination of life table methods and directly modelled changes in disease prevalence.

The two model components make up the Health Impact of Domestic Energy Efficiency Model (HIDEEM; Figure 1)
Figure 2), an exposure-determinant and health impact model.

Other health outcomes that could be related to energy efficiency interventions but were not considered here include cold-related falls, changes in mental health impact (aside from temperature) and some forms of indoor pollutants (e.g., volatile organic compounds, carbon monoxide poisoning, dust mites). However, such evidence can be sparse and the exposure–response uncertain. We have not modelled the impact of cold on respiratory disease (e.g., chronic obstructive pulmonary disease) because the evidence required for robust quantification is still equivocal, we hope to address this in future versions of the model. Also, we have not modelled the risk of overheating on energy efficiency, though this could have an important impact in the future. A difficulty with many empirical studies looking at the health effect of energy efficiency interventions is that the study designs and methods have not been sufficiently robust in their design or controlling for bias so as to draw strong conclusions.

Part 1: Modelling the indoor environment
We developed a model that characterised the indoor environmental conditions of the 2010 English Housing Survey (EHS). The indoor environmental conditions and changes in those conditions related to energy efficiency interventions were modelled using validated building physics and airflow models. The modelling, described in detail elsewhere, used representative archetype dwelling forms (informed by sampling from the EHS) to represent the English dwelling stock. Each of these archetypes was modelled under different levels of air tightness and ventilation systems: window opening only, window trickle vents, extract fans, and combined use of trickle vents and extract fans. A total of 896 archetypes were modelled and matched to the EHS on the basis of dwelling type (e.g., detached, semidetached, terraces and flats), floor area and notional permeability. The result was a model of indoor environmental conditions for a representative sample of English dwellings (see online supplementary appendix 1 for further details).

Dwelling energy performance was calculated as a notional heat loss value. We used an empirical relationship between the dwelling heat loss value and standardised internal temperature (SIT) to predict the bedroom and living room temperature, standardised at an external temperature of 5°C. The SIT is a measure of the thermal condition of the dwelling ranked against all other dwellings, and is a function of the dwelling’s energy and ventilation performance. The estimated average SIT (derived from an average temperature of the living room and bedroom) for each dwelling reflects the observed distribution shown in Oreszczyn et al. The SIT to thermal performance relationship used in the model captures empirical rebound in temperature (e.g., reduced heat flow, changes in occupant heating practices and temperature increases). We used EHS data on dwelling fabric characteristics, heating system type and presence of ventilation systems to determine eligibility for energy efficiency upgrades (see online supplementary appendix 2).

Part 2: Quantification of health impact
We focused on a relatively restricted list of exposures that are supported by reasonably clear epidemiological evidence. The health impact of changes in indoor air
quality and temperature on (cause-specific) mortality was modelled using life table methods based on the IOMLIFET model\textsuperscript{29} but applied to individuals in the EHS data based on their age, sex and specific exposure changes. Life tables were set up using 2010 age-specific population and (disease-specific and all-cause) mortality data for England and Wales from the Office for National Statistics (ONS), with separate life tables set up for males and females.\textsuperscript{30} We modelled changes in five indoor exposures: SIT, STS, indoor and outdoor sources of particulate matter with a diameter of 2.5 μm or less (PM$_{2.5}$), radon and mould; the selected outcomes are listed in table 1. Impacts on morbidity for these same outcomes were estimated from the mortality estimates by applying age-specific and cause-specific ratios of years of healthy life lost due to disability (YLD) to the overall years of life lost (YLL) derived from WHO Global Burden of Disease data.\textsuperscript{31}

Since some of the outcomes are subcategories of others, to avoid double counting we removed deaths in those subcategories from the larger categories. For outcomes affected by more than one exposure, we assumed the relative risks were multiplicative.

We assumed no time lags for cold-related deaths since these would likely to begin to occur within a year. For the other outcomes, a change in exposure would not necessarily lead to an immediate change in mortality in the population. Therefore, we incorporated disease-specific time functions to account for disease onset and cessation lags over time. The time lag functions were based on empirical evidence of the effect of smoking cessation on mortality over time,\textsuperscript{30} and plausible assumptions about disease progression over time (see online supplementary appendix 3).

We separately estimated morbidity impacts on common mental disorders (CMDs) in adults and asthma in children using published estimates of the underlying disease prevalence in the population to which exposure-related relative risks were applied based on changes in SIT and mould growth, respectively (table 1). Mental health benefit is assumed to persist over 10 years (ie, exponential decay to zero over 10 years).

### Model application: 2030 energy efficiency targets

The model was used to examine the effect of energy efficiency retrofits of the type and order proposed under 2030 GHG mitigation pathways for the English housing sector.\textsuperscript{1} Where dwellings were eligible, the retrofits comprised installing double glazing, insulating cavity and solid walls, adding loft insulation, installing new condensing gas boilers, and adding draught proofing to improve dwelling air tightness in leaky dwellings (air leakage rate ≥7 m$^3$/m$^2$/h). In addition, non-operational extract fans in the kitchen and bathroom were repaired and window trickle ventilators\textsuperscript{ii} were installed with glazing upgrades.

We examined three scenarios that addressed ventilation alongside the energy efficiency retrofits (table 2). They were:

\textsuperscript{ii}A small purpose provided opening in a window or building envelope that facilitates ventilation in spaces when large openings (windows and doors) are closed and fans are turned off.
1. Purpose provided ventilation via extract fans and trickle vents (where not already present) was installed to ensure adequate indoor air quality in line with regulations (Regulation);

2. Purpose provided ventilation was installed (or repaired) only for dwellings that exhibit problems of mould or inadequate ventilation as reported in the EHS (∼1.16 million dwellings—see online supplementary appendix 1; Installer Discretion); and

3. No purpose provided ventilation was added except for repairing broken extract fans and trickle vents for double glazing to reflect the lack of guidance surrounding energy efficiency retrofits (No Added Ventilation).

We assumed instantaneous installation for all retrofits in order to illustrate the effect of changes in exposures and associated health effect with all other unrelated conditions held constant. We also assumed that no changes occurred in the underlying health status of the population over time, an assumption which previous work has shown to have only a minor effect on life table calculations.41

Uncertainty analysis

We used Monte Carlo simulation to assess parametric uncertainty in the health impact estimates associated with the determinant of the exposure change (ie, the change in heat loss and air tightness due to each intervention), the exposure–response relationships and the utility weights for each health outcome. We report 95% credible interval estimates based on the 2.5th and 97.5th centiles of results generated from 500 model iterations.42 43 See online supplementary appendix 4 for further details.

We also examined the uncertainty of the model due to two important structural assumptions: (1) the length of life lost in those dying of cold-related causes, and (2) the toxicity of particles derived from indoor sources. For cold, assessing chronic health impacts using exposure–response functions based on time series analyses implies that those who are vulnerable to cold-related risks have the same life expectancy as the population average. This is unlikely to be the case; instead it is likely that the people who die of cold-related events are people who have shorter than average life expectancy (see online supplementary appendix 5 for further discussion). To address this, we have examined the effect of assuming that those vulnerable to cold fall into a ‘high-risk’ subgroup of the population with elevated underlying cardiovascular risk. We then examined the shortening of remaining life expectancy in such a high-risk group as a function of (1) its size as a proportion of the total population (if overall cardiovascular deaths remain the same), and (2) the elevation of risk (relative risk) in the high-risk group compared with the remainder of the population. For particle toxicity, the epidemiology is dominated by studies of outdoor air pollution. However, it is unclear whether the same toxicity should be assumed for particles derived from indoor sources, whose concentration may rise if air tightness is increased. To account for this uncertainty, we performed calculations with and without the inclusion of the estimated effect of particles derived from indoor sources.

There is also uncertainty in the use of the mould severity index (MSI) used in the EHS that is derived from a visual inspection of the occurrence and extent of mould on windows, walls and ceilings. The potential uncertainty of the MSI measurement beyond the simple Monte Carlo treatment of the uncertainty in mould exposure is not examined here.

RESULTS

Indoor environmental exposure levels

The 2030 energy efficiency interventions resulted in improvements in energy performance, as well as appreciable increases in air tightness. The changes in indoor air pollutant concentrations reflected the ventilation
The modelled estimates for the baseline housing stock energy performance and indoor exposures were compared against observed national and sample stock distributions to check the accuracy of the outputs (see online supplementary appendix 1). With the added ventilation, heat losses (33%) and heating energy (32%) were lower, while added ventilation reduced outdoor-generated PM2.5 (-10%) but increased indoor exposure to outdoor-generated PM2.5 (4.2%).

The ‘Installer Discretion’ scenario shows that mitigation measures applied due to perceptible conditions of inadequate ventilation or mould growth were insufficient to have wide benefit (in part due to the relatively small number of dwellings exhibiting these conditions, see online supplementary appendix 1). With the added ventilation, heat losses (33%) and heating energy (32%) were greater compared with the ‘Regulation’ scenario along with a modest increase in indoor temperatures. Outdoor sources of PM2.5 reduced considerably (-10%), but indoor pollutants experienced sizable increases (8% for PM2.5, 34% for radon, 13% for STS, 23% for mould), but increased indoor exposure to outdoor-generated PM2.5 (4.2%).

Under the ‘No Added Ventilation’ scenario, there were still greater reductions in ventilation heat losses. The average indoor pollutant concentrations were higher due to inadequate ventilation or mould growth.
further elevated across the stock compared with scenario 2 (Installer Discretion).

**Health impact of energy efficiency retrofits**

The balance of the overall impact on mortality and morbidity is highly dependent on the assumptions made regarding the level of ventilation to mitigate reduced indoor air quality (table 3; figure 3). Over a follow-up period of 50 years, the net impact of the 2030 energy efficiency interventions under the ‘Regulation’ ventilation scenario resulted in 2241 quality adjusted life years (QALYs) gained per 10 000 persons for the 18.99 million affected dwellings. Selective targeting of ventilation system under the ‘Installer Discretion’ scenario resulted in −539 QALYs per 10 000 persons lost. While no added ventilation had an even greater overall negative impact of −728 QALYs per 10 000 persons lost among the intervention group.

If building regulations were met (scenario 1), the net impact on health is positive primarily because the reduction in exposure to particles of indoor origin is greater than the increase in outdoor-generated particles. Improved indoor temperatures have a net positive effect on cardiovascular disease, though this is dependent on assumptions of the remaining life expectancy of those vulnerable to the effects of cold (see Uncertainty analysis section).

Targeted extract fans and trickle vents in dwellings with a perceptive ventilation problem (scenario 2) offer only moderate modification on the long-term impact on health, a 30% improvement from no additional ventilation (scenario 3). However, despite these interventions, there remained a large number of dwellings that experienced an increase in fabric air tightness.

When no additional ventilation was provided alongside the dwelling energy efficiency retrofits, the increase in indoor sources of air pollutants resulted in a net negative impact on health, despite the reduced ingress of outdoor sources of particulates. Although sensitive to assumptions on the equal toxicity of indoor and outdoor PM$_{2.5}$ (see Uncertainty analysis section), reduced infiltration of outdoor air and increases in exposure to STS, radon and mould risk resulted in a net-negative impact on health.

**Uncertainty analysis**

**Cold-related deaths risk group size**

We use here scenario 2 to illustrate the sensitivity of the health impact estimates to changes in the concentration of cardiovascular risk within the population. Reducing the size of the ‘high-risk’ cardiovascular group in the population reduces the scale of the health benefit due to increased winter temperatures, though the overall impact is modest (see table 4). We illustrate this by concentrating the risk across increasingly smaller proportions of the population (from 100% to 0.1%), selected to represent the full range of plausible assumptions. An assumption of 100% of the excess winter cardiovascular deaths being in the high-risk group (ie, the whole population at risk) could result in a considerable overestimate of the change in the burden of winter time cardiovascular disease, while an estimate of 0.1% (ie, only 0.1% of the population are at risk) would effectively remove all of the potential benefit of increased temperatures for population health. Pending further research, it is difficult to estimate the correct level of adjustment. However, the impact is almost certain to be appreciably less than that implied by using time series coefficients applied without any correction.

**Figure 3** Net mortality and morbidity health effect (quality adjusted life years (QALYs) per 10 000 persons) for all selected exposure-specific diseases after 50 years for the 2030 energy efficiency experiment for different ventilation scenarios (arrows denote 95% credibility intervals). Note: cardiovascular disease is modelled with equal risk across the population and toxicity of indoor and outdoor PM$_{2.5}$ is considered equal and as such the results are likely overestimating the impact—see ‘section, Uncertainty analysis’ for tests (PM$_{2.5}$, particulate matter with a diameter of 2.5 μm or less).
### DISCUSSION

This modelling work shows that predicted changes in indoor environmental exposures following housing energy efficiency interventions of the type being proposed by the UK Government may have an appreciable impact on health. This approach can be applied to different country settings but with regard to existing conditions, and information on the housing stock and households therein.

There is an expectation that retrofits that seek to reduce space heating energy demand will increase indoor temperatures, but such interventions will also affect the dwelling air tightness and its ventilation. Although indicative, our modelling suggests that reducing fabric heat loss and increasing air tightness may reduce exposure to outdoor pollutants and raise indoor temperatures. However, without added ventilation, indoor concentrations are increased with associated adverse health impacts which are greater than those associated with indoor temperatures, leading to an overall negative impact on health. As demonstrated, this conclusion is sensitive to assumptions made about the toxicity of indoor PM$_{2.5}$, and the balance of indoor and outdoor particles on health.


### Toxicity of indoor particulate matter

There is uncertainty about the relative toxicity of particles generated from indoor sources compared with those from outdoor sources. Some evidence suggests these might be as toxic or perhaps even more toxic as particulate matter (PM) derived from outdoor sources. Analysis in which indoor-generated PM$_{2.5}$ was assumed to have no adverse effect on health had a significant impact on the results (see table 5), reducing the overall net health impact by around 78% compared with the base case results (which assumed equal toxicity to outdoor particulates). Though the effect may be uncertain, there is very likely to be some impact from indoor sources and we would stress the need for more empirical studies that measure and assess the toxicity of indoor PM$_{2.5}$, and the balance of indoor and outdoor particles on health.


### Table 4

<table>
<thead>
<tr>
<th>Experiment ventilation scenario 2: ‘installer discretion’</th>
<th>Size of ‘high-risk’ group*</th>
<th>100%+†</th>
<th>1%</th>
<th>0.1%</th>
<th>0.01%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cardiovascular (winter)</strong></td>
<td>63.8 (59.8, 68)</td>
<td>14.5 (12, 17)</td>
<td>1.4 (1, 2)</td>
<td>0.14 (0.1, 0.2)</td>
<td>0.014 (0.01, 0.02)</td>
</tr>
<tr>
<td><strong>Heart attack</strong></td>
<td>34.1 (28.1, 40)</td>
<td>7.1 (6, 8)</td>
<td>0.71 (0.6, 0.8)</td>
<td>0.071 (0.06, 0.08)</td>
<td>0.0071 (0.006, 0.008)</td>
</tr>
<tr>
<td><strong>Stroke</strong></td>
<td>232.1 (279, 185.5)</td>
<td>50.6 (45, 56)</td>
<td>5.06 (4.5, 5.6)</td>
<td>0.506 (0.45, 0.56)</td>
<td>0.0506 (0.045, 0.056)</td>
</tr>
<tr>
<td><strong>Cardiomyopathy</strong></td>
<td>449.6 (404.4, 554.2)</td>
<td>99.9 (90.9, 110)</td>
<td>9.99 (9.09, 10.99)</td>
<td>0.999 (0.909, 1.099)</td>
<td>0.0999 (0.0909, 0.0999)</td>
</tr>
<tr>
<td><strong>Lung cancer</strong></td>
<td>74.3 (67.1, 81.5)</td>
<td>14.9 (13, 16)</td>
<td>1.49 (1.3, 1.6)</td>
<td>0.149 (0.13, 0.16)</td>
<td>0.0149 (0.013, 0.016)</td>
</tr>
<tr>
<td><strong>Common mental disorder</strong></td>
<td>2.7 (2.8, 4.1)</td>
<td>0.54 (0.52, 0.56)</td>
<td>0.054 (0.052, 0.056)</td>
<td>0.0054 (0.0052, 0.0056)</td>
<td>0.00054 (0.00052, 0.00056)</td>
</tr>
<tr>
<td><strong>Asthma (children)</strong></td>
<td>1.3 (1.4, 1.4)</td>
<td>0.26 (0.25, 0.27)</td>
<td>0.026 (0.025, 0.027)</td>
<td>0.0026 (0.0025, 0.0027)</td>
<td>0.00026 (0.00025, 0.00027)</td>
</tr>
<tr>
<td><strong>Net QALYs</strong></td>
<td>569.5 (−724.2, 466.7)</td>
<td>−134.3 (−143, −126)</td>
<td>−13.43 (−14.3, −12.6)</td>
<td>−1.343 (−1.43, −1.26)</td>
<td>−0.1343 (−0.143, −0.126)</td>
</tr>
</tbody>
</table>

*Proportion of the population in the group assumed to be at high risk for cardiovascular events.

†100% equivalent to whole population equally at risk.

QALYs, quality adjusted life years.
prevalence of CMD in the population, any small shift can be highly influential on the results. While there is very likely to be benefit that accrues beyond a single year and maybe a seasonal effect for a period afterwards, the long-term benefit will likely be affected by the risk of reoccurring episodes of mental health driven by factors other than thermal environment.

The underlying assumptions regarding housing air tightness and occupant ventilation practices (eg, window opening behaviour) are both extremely important. The EHS shows that 71% of homes have no extract fans (or working extract fans); in other words, these homes are naturally ventilated and thus, the exposure to indoor-generated pollutants will be highly determined by the air tightness of the dwelling and the practices of the occupants. Our model has examined the uncertainty of these practices on our estimates and therefore, provides a reasonable spread on the likely true impact. From our scenarios, we found that added ventilation accompanying efficiency retrofits mitigated the health risk associated with increased air tightness (scenario 1), but that this mitigation must be applied beyond ‘problem homes’ (scenario 2), only the widespread installation of ventilation systems results in a net benefit to health (scenario 1), and providing no additional ventilation poses a potential risk to health (scenario 3).

The provision of added ventilation to offset potential increases in indoor concentrations of pollutants following fabric energy retrofits is an important issue for public health. While the spirit of the building regulations suggests that adequate ventilation should be provided following changes to a dwelling, there is no explicit guidance for installers on what and when to install such systems. The Housing Health and Safety Rating System provides an ‘after-the-fact’ route through which remediation of poor indoor air quality could be addressed, but it is both unlikely and undesirable to rely on this system to address issues that could otherwise be avoided. Clearly assumptions on how a household ventilates their dwelling will have an important impact on creating a healthy indoor environment. Dwellings with higher ventilation rates have been shown to have reduced health burdens, though the association with air change rates and specific diseases can be equivocal. Occupant ventilation practices have also been shown to be counter-productive to creating a healthy indoor environment. A study of Dutch households showed that many neglect the annual maintenance required to ensure that ventilation system operation is not compromised. Education around ventilation will be essential to minimise exposure to indoor pollutants following retrofits. Our work highlights that the potential health impacts following efficiency retrofits are not necessarily positive and that there may be risk trade-offs that will depend on the retrofit installation regulatory framework. Having stronger regulation around energy efficiency retrofits and ventilation will help to realise multiple benefits (eg, energy savings and health).

### STRENGTHS AND LIMITATIONS

Modelling studies provide a method of examining complex problems by drawing together data from a range of sources in order to explore the potential impact of interventions on population health. While quantifying the potential health impact of policy options is preferable over qualitative assessment, doing so is subject to several difficulties, primarily the availability of evidence and the potential to add scientific credibility to uncertain predictions. The modelling also involves many uncertainties. For instance, the limited set of observed data on how such retrofits affect indoor air quality remains an impediment, with only a few studies looking at the determinants of indoor air quality (eg, infiltration). There is a paucity of evidence relating to some of the most important health outcomes—especially in relation to cold. In the overall balance of health calculations, morbidity impacts are potentially larger than those of mortality, for example, the effect of improved temperatures on CMD, but the evidence is still uncertain, and this gap in the research evidence should be addressed.

The modelling results are presented as QALYs; however, it is clear that these changes in disease

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**Table 5** Cumulative health effect after 50 years for indoor PM$_{2.5}$ toxicity equal to outdoor sources and with no effect of indoor PM$_{2.5}$ under the 2030 energy efficiency retrofit experiment for scenario 2 ‘installer discretion’

<table>
<thead>
<tr>
<th>Net QALYs</th>
<th>Indoor particulate matter toxicity</th>
<th>Experiment ventilation scenario 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Equal to outdoor</td>
<td>No effect</td>
</tr>
<tr>
<td></td>
<td>Mean per 10 000 persons (95% credibility intervals)</td>
<td>Mean per 10 000 persons (95% credibility intervals)</td>
</tr>
<tr>
<td>Cardiovascular (winter)</td>
<td>68.8 (56.8, 80.7)</td>
<td>81.6 (69.8, 93.4)</td>
</tr>
<tr>
<td>Heart attack</td>
<td>−232.1 (−279.1, −185.2)</td>
<td>−186 (−225, −147)</td>
</tr>
<tr>
<td>Stroke</td>
<td>−257.6 (−309.7, −205.5)</td>
<td>−212.1 (−255.1, −169)</td>
</tr>
<tr>
<td>Cardiopulmonary</td>
<td>−44.3 (−83.4, −5.6)</td>
<td>200.8 (170.5, 233.5)</td>
</tr>
<tr>
<td>Lung cancer</td>
<td>−74.9 (−92.9, −57.4)</td>
<td>−47 (−59.8, −34.5)</td>
</tr>
<tr>
<td>Common mental disorder</td>
<td>2.7 (2.8, 4.1)</td>
<td>2.8 (2.9, 4.1)</td>
</tr>
<tr>
<td>Asthma (children)</td>
<td>−1.3 (−8.4, −4.3)</td>
<td>−1.3 (−8.1, −4.2)</td>
</tr>
<tr>
<td>Net impact</td>
<td>−538.6 (−677.9, −399.3)</td>
<td>−161.2 (−240.3, −82)</td>
</tr>
</tbody>
</table>

PM$_{2.5}$, particulate matter with a diameter of 2.5 μm or less; QALYs, quality adjusted life years.
outcomes would have an impact on health and social care services beyond these utility estimates. As the average age of the UK population increases so too does the demand on health services. Preventative actions, such as improving energy and ventilation performance, may help to mitigate some of this demand.

The exposure modelling in this experiment concentrated on indoor conditions. The experiment did not alter outdoor pollutant concentrations related to proposed energy supply decarbonisation, which may reduce outdoor levels of particulate matter in the future. This would further tip the balance towards installing mitigating ventilation systems so as to dilute ‘stale’ indoor air. Refining the model to include assumptions on energy systems and transport could further improve the estimates of the potential health impact associated with UK’s GHG abatement measures.

CONCLUSIONS AND POLICY IMPLICATIONS

On balance, if properly implemented, actions to mitigate climate change through energy efficiency in housing can have benefits to health by reducing exposure to cold and outdoor air pollutants. They will also offer indirect health benefits by providing more resilience to protect indoor thermal conditions during extreme cold and heat events. Modelling studies of the type presented here are needed to ensure housing policies are developed in ways that capitalise on this potential for improving health. Such studies, however, should be used with acknowledgment of their uncertainty and limitations, and do not supplant the need for well-designed empirical studies that can validate models and offer policymakers more evidence, and provide greater confidence around policy impact.

We have shown that, unless specific remediation is used, reducing the ventilation of dwellings will improve energy efficiency at the expense of increased exposure to indoor air pollutants and risk to health. However, an important conclusion of this work is that, with careful attention to retrofit installation and ventilation practices, these potential negative impacts can be removed.

The policy agenda and evidence base on the health impact of home energy efficiency is still evolving. Guidance for installers regarding adequate levels of ventilation to protect health is now needed before the large-scale introduction of energy efficiency measures into the housing stock.

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Contributors IH developed the integrated health and exposure model, and was responsible for developing the experiment and crafting the text. JM and ZC developed the health model and contributed to the text. PD, BJ and CS all developed portions of the exposure models and contributed to the text. MD and PW were project leaders, guided the study design and contributed to the text.

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Data sharing statement All data used in the study are drawn from publicly available sources, these include: English Housing Survey (UK Data Archive), IOMLIFET (Institute of Occupational Medicine), England and Wales Mortality Data (ONS), and the Warm Front Data (UK Department of Energy and Climate Change (DECC)). Special request to DECC is needed for access to Warm Front.

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