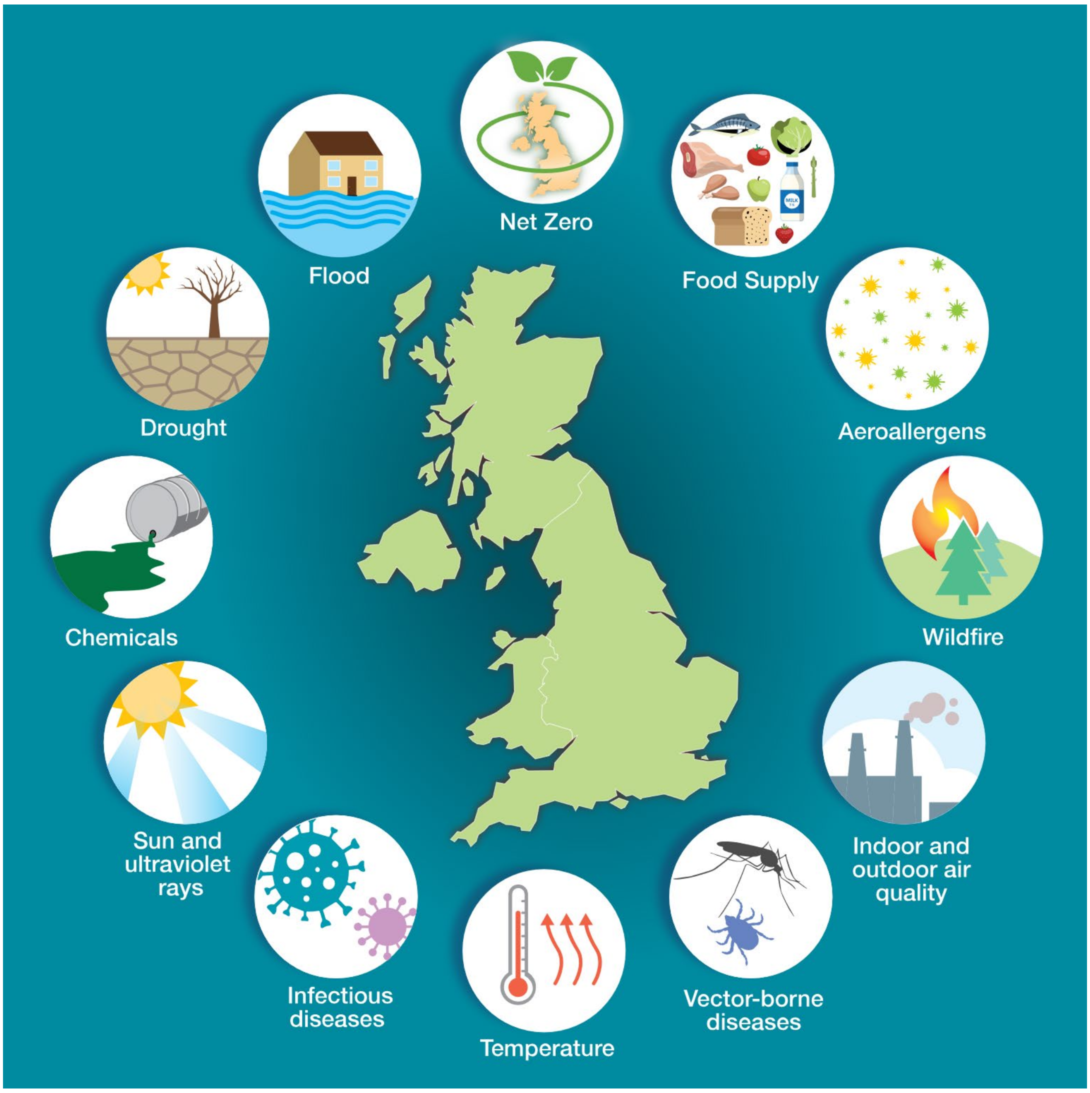
UK Health Security Agency

Health Effects of Climate Change (HECC) in the UK: 2023 report

Chapter 5. Impact of climate change policies on indoor environmental quality and health in UK housing



Summary

People in the UK spend on average more than 95% of their time in indoor environments, and 66% of time in their own homes. Chapter 5 presents a review of evidence on the impact of climate change policies on indoor environmental quality and health in the UK. The chapter synthesises new evidence published since the last 'Health Effects of Climate Change in the UK' report, including the impact of climate mitigation and adaptation policies. The chapter was written by scientists at the UK Health Security Agency (UKHSA), University College London, University of Nottingham, University of Strathclyde and London School of Hygiene and Tropical Medicine.

The UK building stock is among the oldest in Europe, and large-scale home retrofits are required to reduce energy demand and achieve net zero. This can include insulating external walls, double or triple glazing, low-carbon heating with heat pumps, and draught proofing. Arrangements for new builds include high levels of airtightness with mechanical ventilation and heat recovery, cooling measures, triple glazed windows and low-carbon heating. However, energy efficiency measures, if poorly installed, may increase indoor air pollutant concentrations from internal sources, such as carbon monoxide, particulate matter, nitrogen dioxide, radon and biological contamination (for example, allergens, mould, viruses and bacteria). Exposure to increased levels of these contaminants is associated with adverse health effects including respiratory, cardiovascular or neurological conditions and cancer. Ventilation is necessary to maintain good indoor air quality and reduce risk from some infectious diseases, although this is outside of the scope of this chapter. Maintaining indoor temperatures at recommended levels and reducing exposure to air pollution should also be considered.

This chapter highlights several key insights for public health. Measures to mitigate climate change such as passive or low-carbon heating and cooling, energy efficient lighting, and solar energy will enable existing homes to become more energy efficient, may help alleviate fuel poverty and improve thermal comfort in winter. However, such measures also increase building airtightness and without accompanying improvements in ventilation, retrofitted homes may experience degraded indoor environmental quality. Overheating in summer is associated with adverse physical and psychological health impacts. The effects of exposure to noise from mechanical ventilation are not yet understood; however, the ingress of environmental noise from transport has adverse psychological and physiological impacts on health, such as sleep disturbance and cardiovascular and metabolic diseases.

People spend a large proportion of their time indoors and, therefore, the indoor environment is an important determinant of health. Further work is needed to increase awareness among people and professionals and to develop interventions to reduce exposure to indoor air pollutants.

The chapter highlights 2 priority research gaps and priorities, including the need to:

- assess the impact of energy efficiency measures and behaviour on health, through systematic surveillance of IEQ, with cohort studies and citizen science approaches
- evaluate the impact of energy efficiency retrofitting on indoor environmental quality with a particular focus on high-risk settings and populations

UKHSA together with the Office for Health Improvement and Disparities (OHID), and the Department for Levelling Up, Housing and Communities (DLUHC) has jointly published guidance on damp and mould for rented housing providers. This is part of the government's response to the Prevention of Future Deaths report, following the death of a 2 year old child from a severe respiratory condition due to prolonged exposure to mould in his home. UKHSA has a well-developed radon survey capability that is available across the UK. Survey results feed into the development and refinement of radon maps that are available through UKHSA working with the British Geological Survey.

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1. Background

The impact of climate change adaptation and mitigation policies on indoor environmental quality have been discussed to varying degrees in all 3 previous 'Health Effects of Climate Change in the UK (HECC)' reports (1 to 3). The third report in 2012 devoted a whole chapter to indoor air quality and provided a comprehensive overview (3). The 2012 report was followed by a publication in 2015, which noted that much of the impact of climate change in the UK is likely to amplify existing risks related to heat exposure, flooding, and chemical and biological contamination in buildings (4).

As the climate changes in the UK, buildings that were designed to operate under the previous climatic conditions, may not function well under the changing and future conditions, affecting the health of those who live, work, study, or play in them. The 'Third UK Climate Change Risk Assessment (CCRA3)' technical report concluded that "there is very little evidence for the impact of climate change on indoor air quality" (5).

With the UK population spending, on average, over 95% of their time in indoor environments and 66% of their time in their own homes (6), the built environment has a significant modifying effect on population exposure and health. According to previously published reviews (4, 7 to 9), climate change is likely to affect indoor environmental quality and hence health and comfort of occupants, through changes to outdoor environmental conditions (including higher temperatures, more frequent and severe heatwaves, wildfires, severe storms, and increases in outdoor ozone levels and outdoor pollens); mitigation (to improve energy efficiency in buildings) and adaptation measures (including the provision of mechanical ventilation to address thermal comfort and indoor air quality (IAQ) (7)), which can often have unintended consequences for indoor environmental quality (IEQ); and occupant behaviour, including indoor activities, the use of windows and mechanical ventilation.

This chapter aims to provide the latest knowledge on the impact of mitigation and adaptation policies related to climate change, first on building regulations, and consequently on indoor environmental quality in the UK and the role of occupants on IEQ. Improving home energy efficiency will normally improve occupant thermal comfort, particularly in colder weather; however, if poorly installed, it may lead to unintended consequences in terms of deterioration of indoor air quality and biological contamination (including damp and mould), building overheating, and noise from ventilation systems, batteries and pumps. This chapter reports on indoor environmental quality issues in the UK, identifies reasons of concern in terms of health, and discusses interventions that may help to minimise health risks.

2. Impact of climate change policies on buildings

2.1 Building regulations

The third UK CCRA technical report highlighted that IEQ is highly affected by net zero policies, which aim to reduce carbon dioxide (CO_2) emissions from the housing sector by introducing energy efficiency measures (5). This section provides the background on current legislation and net zero policies and their impact on IEQ.

It is estimated that the residential sector was responsible for around 16% of greenhouse gas (GHG) emissions in the UK in 2020, with CO_2 being the most prominent gas from this sector (97%) (10). The use of natural gas for space heating and cooking is the main source of emissions from the residential sector (10). Compared to 2019, the emissions from the residential sector increased by 1.0% as more people stayed at home during the COVID-19 pandemic (10).

A report by the Climate Change Committee (CCC) emphasised that near-complete elimination of GHG emissions from UK buildings is required to meet climate change targets (11). Despite a quarter more homes having been built since 1990, the overall total emissions from the residential sector decreased by about a fifth in the years leading up to 2017, due to a combination of "tighter building and product standards, in particular better boilers; the uptake of insulation and other energy efficiency measures, mainly delivered through obligations on energy suppliers; and greater awareness of potential energy savings" (12). However, declines in emissions from the UK's 29 million homes has now stalled.

The government recently made a significant update to the 'Building Regulations for England'. The current guidance covers ventilation, conservation of fuel and power, overheating requirements of building regulations, and infrastructure for the charging of electric vehicles; these are as set out in Part F (13), Part L (14), Part O (15) and Part S (16) (FLOS) of the Building Regulations, respectively, for dwellings and buildings other than dwellings. The updated building regulations FLOS have been in force since 15 June 2022. This guidance provides intermediate uplift to existing energy efficiency standards and is a stepping stone towards the government's new Future Homes Standard (due to be introduced in 2025). The Future Homes Standard, which builds on the Clean Growth Building mission, will aim to future-proof new build homes with low carbon heating and high levels of energy efficiency. The uplift to Approved Document F aims to ensure that ventilation provision is not reduced when energy efficiency work is carried out in existing homes. For both new homes and existing homes, there are mandated checklists for installations of mechanical ventilation products, together with a guidance on the importance of ventilation. All replacement windows should be fitted with trickle vents unless a) there is an alternative form of ventilation, such as air bricks or whole house mechanical ventilation with heat recovery (MVHR) or b) the ventilation is not worse than before the works were done.

The uplift to Part L includes updated insulation requirements for new homes (assessed under a new Standard Assessment Procedure (SAP) calculation, SAP 10). For existing homes, minimum new fabric efficiency standards will now apply if new or replacement thermal elements, such as windows and doors, are introduced to existing homes, aiming at energy loss through the building fabric (U-values). There is also new guidance for glazing in extensions, improvements for lighting design (which take no account for the need to adjust 24-hour lighting levels or lighting efficacy calculations for health) and a new maximum flow temperature requirement for a central heating system (55°C instead of over 75°C).

The main intention of Part O is to limit excess solar gain in new and existing homes and remove excess heat. Assessment can be done through either the Simplified Method or the Dynamic Thermal Modelling Method. A standard is also included for the maximum amount of glazing allowed in a single room. Both Part F and Part O require the consideration of the potential for noise impacts. Part F specifies recommended noise limits for mechanical ventilation operating under normal conditions, which can be achieved through appropriate design and installation. It also requires assumptions on whether openable windows are appropriate for purge ventilation to take into consideration the level of external noise. Part O states that the overheating mitigation strategy should take account of the likelihood that windows will be closed during sleeping hours if noise from outside exceeds specified limits. These are good examples of safeguards that reduce the risk of unintended consequences by encouraging a multi-pollutant assessment.

The Future Homes Standard will set out energy and ventilation standards for non-domestic buildings and existing homes and includes proposals to mitigate against overheating in residential buildings. The new Future Homes Standard should ensure that all new homes built from 2025 will produce 75% to 80% fewer carbon emissions than homes delivered under current regulations. However, the greatest challenge is not in setting but in complying, monitoring, and enforcing new standards.

The Scottish Government recently introduced major changes to the Scottish Building Standards Technical Handbooks for domestic and non-domestic buildings, which came into force on 1 February 2023 (17). These updates include significant changes to Section 3 (Environment), which includes guidance for ventilation systems and new standards for overheating; Section 6 (energy), which includes a 32% reduction in carbon emissions over previous standards, tighter limiting fabric standards, mandatory airtightness testing in all homes and adoption of SAP 10 methodology, and Section 7 (sustainability), which changes guidance of CO_2 emissions (17).

2.2 Energy efficiency measures

The UK building stock is among the oldest in Europe, with half of all non-domestic premises built before World War 2. The number of homes increased from 18.8 million in 1970 to 27.8

million households in 2020, which included an increase of 5.9% over the last 10 years alone (18). The use of materials and building practices have changed over time, resulting in general building archetypes. From the late 20th century onwards, these comprise standard clay cavity brick wall construction, modern reinforced concrete and steel structures and a growing use of glazed fabrics in multi-storey buildings (19). Some retrofit uses external cladding, which has been shown to be a fire hazard. The 'Building a Safer Future' report was followed by a ban in England on the use of unsafe aluminium combustible materials (ACM cladding) in December 2018, in high-rise residential buildings. One study, applying a GIS-based domestic energy map, identified that approximately 75% of 431 dwellings in Oxford were suitable for a whole house retrofit package, which would result in around 90% mean energy reduction over baseline (20). In addition, 1930s semi-detached homes in areas with low household income were identified as having the greatest need for retrofitting, followed by 1930s terraced housing, in areas with median level of household income (20).

Mitigation measures have been proposed for existing and newly built homes that would help prepare the UK building stock for the impacts of climate change and enable the UK government to meet its legally binding emissions targets by 2050 (11). For existing buildings, these include insulation of external walls, draught proofing of the building envelope, double or triple glazing with shading, low-carbon heating with heat pumps, highly energy-efficient appliances and water-efficient devices, green space and flood resilience and resistance. For new homes, these include high levels of airtightness with mechanical ventilation and heat recovery, cooling measures, triple glazed windows and external shading, low-carbon heating and shift to electrification, water management and flood resilience and resistance.

Achieving net zero targets require large-scale retrofits of homes to reduce energy demand. Current technology and energy efficiency measures include retrofit of the building fabric (such as loft, cavity, wall and floor insulation, draught proofing and upgrading windows to highly efficient double or triple-glazed) to minimise unwanted heat losses, using low-carbon technologies for heating (MVHR and cooling, replacing natural gas boilers with heat pumps, heat networks, smart electric heating and hydrogen boilers) and exploiting solar energy (21), and best use of daylight and energy-efficient lighting. These interventions can help new and existing homes to transition to low-carbon and ultra-energy efficiency, while reducing energy consumption through improvements can reduce energy costs and consequently fuel poverty (22).

3. Climate change, indoor air quality and health outcomes

Energy efficiency measures aiming to reduce unwanted air leakage, may increase indoor air pollutant concentrations emitted from indoor sources, including carbon monoxide (CO), particulate matter (PM), nitrogen dioxide (NO_2), chemicals such as volatile and semi-volatile organic compounds (VOCs and SVOCs), formaldehyde (HCHO), radon, and biological contamination (including allergens, viruses and bacteria, mould). They may also decrease indoor concentrations of some outdoor air-generated pollutants. The determinants of exposure to various pollutants, associated health impacts and proposed interventions are briefly discussed below, and are primarily based on the current review and have been extensively discussed in the recent reports by the National Institute of Health and Care Excellence (23), the Royal Society of Paediatrics and Child's Health (24), Defra's Air Quality Expert's Group (25), the report by the Chief Medical Officer for England (26 to 28), as well as other organisations who published guidance on IAG monitoring or sampling (Institute of Air Quality management (29); Chartered Institute of Building Services Engineers (30)).

3.1 Determinants of exposure

IAQ is affected by various factors, including ambient air or environment, urban planning and layout, indoor sources, ventilation, hygrothermal conditions, and occupant behaviours and activities (24, 31), as well as indoor air chemistry (32). The different factors affecting IAQ are reviewed below.

3.1.1 Ambient air and environment

Buildings in urban areas are exposed to air pollutants from various outdoor air pollutant sources. Of particular concern are PM and NO_2, which are generated from transport (petrol and diesel engine emissions along with tyre and brake wear), housing and industrial activities (33), as well as secondary air pollutants, such as ozone (O_3), formed through chemical reactions between other pollutants in the atmosphere. Weather conditions (including wind speed and direction, thermal stratification, heat island phenomenon) affect infiltration and ventilation. The infiltration of outdoor air pollutants defines the background concentrations of air pollutants indoors, especially in the absence of strong indoor sources. The median modelled indoor/outdoor (I/O) ratios for NO_2 for dwellings in London, for example, is 0.41 (99% CI: 0.34 to 0.59), while median I/O ratios for $PM_{2.5}$ is 0.60 (99% CI: 0.53 to 0.73) (34). This is consistent with estimates from an earlier modelling study (35).

Radon is a radioactive noble gas that is produced by the radioactive decay of radium and uranium that occur naturally in rocks, soils and the materials into which they are made, and is also present in water and natural gas (methane, CH_4). All buildings and enclosed spaces will contain some radon (36). The highest radon levels in buildings are those in contact with particular geologies that either contain high concentrations of radium or uranium or are porous. Reduced or unbalanced ventilation leads to increased accumulation of radon levels indoors. Basements and cellars, which by definition have ground contact with at least one wall, typically show higher radon levels than surface buildings.

Outdoor sources are important drivers for indoor concentrations of environmental biological contaminants such as fungi, pollen and bacteria. These are in turn affected by climate and seasonal variations, with climatic changes related to temperature, humidity, rainfall, and atmospheric levels of CO_2 likely to affect the species distribution and growth rates. For example, plants can produce more pollen at elevated levels of atmospheric CO_2, which also increases spore production in some fungal species, with increases observed at higher temperatures (37, 38).

3.1.2 Urban planning and urban layout

Urban planning and urban layout define air pollutant emissions near the ground, as well as dispersion in urban areas; some urban layout types (such as street canyons) can trap air pollutants limiting dispersion. The location, type and number of pollution sources within an urban area (for instance junctions, combustion plants and ventilation discharges) affect air pollutant levels in building façades, together with building location, size and orientation in relation to other buildings. Some shapes of buildings, such as tall buildings or those with courtyards or enclosed spaces, have more marked effects than others on dispersion of local pollution sources (39).

3.1.3 Indoor sources

Method of cooking (both the fuel and the way that food is prepared (frying or boiling)) is an important indoor source of PM, NO_2, VOCs and other pollutants, whose concentrations can vary dramatically from one home to another, depending on occupant activities (40). Carbon monoxide (CO) may be generated from malfunctioning fuel burning stoves (wood, kerosene, natural gas, propane), fuel burning heating systems (wood, oil, natural gas) and from blocked flues connected to these appliances. Appliance malfunction may be due to faulty installation or lack of maintenance and proper use (41).

The primary particle emissions from cooking may grow into a specific particle size and disperse within the home where they can take up SVOCs from consumer products (such as personal care and cleaning) and building materials. In addition, the volatile fraction of cooking emissions can undergo reactions indoors that may produce particles, whereas a large fraction of indoor PM from cooking is likely to deposit on indoor surfaces (42). Apart from cooking, other indoor sources of PM include vacuum cleaning, dusting, smoking, incense and candle burning.

Indoor CO concentrations are dominated by infiltration of outdoor air and, in the absence of indoor sources, indoor concentrations will follow those outdoors, as CO is not deposited indoors, but with a time delay of 20 to 30 minutes (35). A monitoring study shows that there is a correlation between NO_2 and CO in homes with the highest readings, where gas was the main fuel for cooking and heating (43). The dwelling type, main fuel type, floor area and how well ventilated a home is, define the CO exposure from indoor sources; bungalows, terraced homes, and flats are typically found to have higher indoor levels, whereas spaces with working extractor fans for gas cooking have significantly lower CO exposure (44). A comprehensive year-long monitoring study in a very large number of UK homes reported mean I/O ratios for NO_2 of 0.6 to 0.7 in homes without gas cooking, but 1.4 for kitchens and 0.9 for living rooms in homes with gas cookers (45).

Apart from the cooking activity, chemicals (VOCs, SVOCs and HCHO) are widely used in construction and building products (such as insulation materials, paints, varnishes, waxes, solvents), in household consumer products (for instance, detergents, cleaning products, air fresheners and personal care products) and are also emitted while using electronic devices such as photocopiers or printers (19, 46 to 48). Public Health England (PHE) published UK indoor air quality guidelines for 11 selected VOCs for the first time (49) which are cited in the revised building regulations Approved Document F that allow the designers "to assess ventilation strategies against the individual VOCs informed by PHE", given appropriate source control in the first place (13).

3.1.4 Ventilation

A fundamental way to maintain good IAQ is ventilation. However, ventilation is hard to simplify. If the ventilation rates are too low, indoor air pollution sources will dominate, but if they are too high, it will consume excess energy and outdoor pollution sources will dominate (42). The installation, operation and maintenance of the ventilation system determines its effectiveness. Mechanical ventilation systems include mechanical extract ventilation (MEV), MVHR, and demand-controlled ventilation (DCV). The golden rule has always been "build tight and ventilate right", essentially meaning that all buildings should have purpose-provided ventilation rather than relying on infiltration of air.

Background ventilators (such as trickle vents and air bricks in walls or windows) are natural ventilation devices and a supplement to operable windows. Their main performance concerns are the ventilation rate, thermal insulation, acoustic resistance, water tightness, and air permeability; therefore, the trickle vents can affect energy performance in buildings and compromise the thermal comfort of occupants (50). A modelling study (51) showed that more than 98% of English houses are too airtight to sufficiently dilute $PM_{2.5}$ concentrations below the WHO guideline of 25 micrograms per cubic metre ($\mu g/m^3$) (at the time of the publication; currently $15 \mu g/m^3$) solely through background ventilation. Controlled ventilation is required in all domestic kitchens, while ventilating during cooking plus 10 minutes after has a significant effect.

Various studies evidence the prevalence of poor ventilation in homes (52). In a monitoring study for the Ministry of Housing, Communities and Local Government (now the Department for Levelling Up, Housing and Communities, DLUHC), only a small number of naturally ventilated homes met the minimum ventilation provisions recommended in Approved Document F (43). In homes with continuous mechanical extract, only one home met the guidance published in Approved Document F with respect to both continuous extractor fan air flow rates and trickle ventilator provision, with the extractor fan flow rates being lower than those recommended (43).

3.1.5 Hygrothermal conditions

Hygrothermal conditions indoors are affected both by outdoor conditions and occupant activities (such as heating and moisture production), building characteristics (insulation or cold surfaces), and water leaks (from indoor and roof pipes) that may increase damp, and ventilation which could dilute indoor sources of moisture. However, poorly maintained or designed mechanical ventilation or air conditioning systems may increase the risk of biological contamination indoors.

Besides the direct impacts of climatic changes on outdoor and indoor hygrothermal conditions potentially affecting the species distribution and population growth of biological contaminants, indirect effects are also important. For example, wetter winter conditions could lead to indoor damp, whereas higher outdoor temperatures may increase the take-up of mechanical ventilation or air conditioning, which in turn may increase the risk of biological contamination if the systems are not suitably installed or maintained (53).

Biological contamination in buildings includes a variety of pollutants; this section largely discusses house dust mites (HDM), fungi (mould), and bacteria. Other biological contaminants related to insects, vermin, allergens from pets or indoor airborne transmission of infectious diseases are not discussed here. Hygrothermal conditions indoors, including within microclimates of habitats such as carpets, mattresses, soft furnishings and surfaces are also important determinants of contamination from fungi and dust mites which thrive in humid and warm environments, with some variation across species; for example, *Dermatophagoides pteronyssinus* is more susceptible to desiccation than *Dermatophagoides farinae* (54). Furthermore, milder winters are likely to increase HDM population growth and alter species variety, whilst changes in humidity in northern latitudes will increase the numbers and species of HDMs (54). On the other hand, humidity affects the interactions between fungi and HDM, whereby relative humidity levels over 90% lead to disproportionate growth of fungi at the detriment of HDM populations (54).

3.1.6 Occupant activities

Occupants have an important role to play, as their activities may generate indoor air pollutants and moisture (23). These include cooking without using an extractor fan, cleaning without increasing ventilation, smoking indoors, drying clothes indoors, wood burning in open fireplaces, having a bath or shower without using ventilation, doing DIY without increasing ventilation, and keeping trickle vents closed or blocked (55).

Occupants may also be a source of biological contaminants indoors, for example by shedding microbes (including pathogens) or carrying them on their clothes thus moving them from one environment to another. Since contaminants arising from biological pollutants can accumulate over time, older properties or furnishings can pose a higher risk, although cleaning practices could partly help in reducing such risk. The presence of cats or dogs in the home and high number of occupants affect concentrations of endotoxins levels in mattress dust in European settings. However, a multi-centre study found that housing characteristics and meteorological factors explained only a small proportion of the variation in endotoxin levels measured in mattresses dust across 22 study centres, with the larger factor being (high) outdoor summer temperatures (56). Other studies found that endotoxin levels in settled floor dust were also affected by building age, cleaning, presence of carpets, farm or rural living, and relative humidity, with cats and especially dogs being a major source of endotoxin both in settled dust and indoor air (57). This is an emerging field and further research is needed on mechanisms and pathways and who exactly is affected (58 to 60).

A review study concluded that households of low socio-economic status in high-income countries often experience higher levels of indoor PM, NO_2, VOCs and environmental tobacco smoke. Higher radon concentrations were found in homes with a greater material wealth; higher incomes tend to favour warmer homes and energy-efficiency measures, both of which increase indoor radon levels. Inequalities in exposures may arise via poor quality housing, a lack of awareness regarding the harm of indoor second-hand smoke, the location of housing near congested roads, and higher occupant density resulting in greater re-suspension of particles, whereas radon levels were principally explained by geological variables (61).

3.1.7 Indoor chemistry

In indoor environments, both gas-phase and surface chemical reactions may occur, which may be similar to those in the outdoor air, but occur under typical indoor conditions: less light, more available surface area for reactions, and limited timescale for reaction, due to exchange with outdoor air (62). As reported in (25), much of the indoor gas-phase chemistry is driven by oxidation reactions of VOCs, particularly with O_3 and hydroxyl radicals (OH) and to a lesser extent by nitrate radicals (NO_3) and chlorine (Cl) radicals. Whereas the OH oxidation of VOCs dominates outdoors, O_3 is a key driver for oxidation indoors, due to lower light levels; the extent of chemistry indoors can change with the location, time of year and time of day, which all affect indoor O_3 concentrations. Gas phase reactions that have received particular attention are the ozone-terpene reactions indoors; O_3 is penetrating indoors from outdoors, or is emitted from indoor sources, whereas terpenes are emitted from consumer cleaning products. Their reactions generate short-lived species (such as radicals) and longer-lived species in both the gas- and condensed-phases (63). Another type of indoor reactions are photolysis, which rely on attenuated light from sunlight outdoors, indoor lighting and UV-C sterilization devices and form key species: O_3, nitrous acid (HONO) and HCHO. Finally, heterogeneous reactions forming particles have also received attention. Particles are emitted from combustion sources (cooking or smoking) or penetrating from outdoors. However, they may also derive from chemical reactions, in which semi- or non-volatile products of the gas phase oxidation of volatile organic compounds by OH, O_3 or NO_3 transfer from the gaseous to the aerosol phase, forming secondary organic aerosols (SOAs) indoors. Type, quantity and dampness of surfaces are important drivers of indoor chemistry, both for deposition but also for reactions and for generating new products. The presence of people has an impact on indoor air chemistry, including decreases in O_3 concentrations and increases in VOC and SOA concentrations (62).

3.2 Health effects

Systematic reviews by health organisations have highlighted the health risks associated with poor IAQ at home and school (23, 24). Both reviews revealed that indoor air pollutants, including PM, NO_2, HCHO, VOCs and biological contamination generated from indoor sources, can trigger or exacerbate asthma, irritation, other respiratory or cardiovascular conditions, and may even have carcinogenic effects. Focusing on VOCs, a recent systematic review concluded that exposure to aromatic hydrocarbons, alkanes and aldehydes are associated with respiratory health effects, exposure to some chlorinated hydrocarbons with cardiovascular neurological and carcinogenic health effects, while esters and terpenes are irritants (47).

There has been extensive and continuous work on the health effects of CO poisoning as well as efforts from the government to reduce the risk of CO exposure (64). This may be acute or chronic and can occur unintentionally or intentionally (self-harm), may have effects on the cardiovascular and neurological systems and may lead to death (41). Unintentional non-fire-related CO exposure is a serious public health issue, and faulty gas boilers in homes is the greatest source of exposure (65), where the most frequent underlying factor is inadequate ventilation of exhaust gases (66). During 2013 to 2021, there were around 20 deaths per year from accidental CO poisoning in England and Wales (64).

Reviews on the effects of exposure to solid fuel burning in higher-income countries, such as the UK, show that there is limited evidence that indoor exposure to wood burning is associated with asthma and respiratory infections in children (67), and with an increased risk of lung cancer and COPD in adults. For other respiratory outcomes, the results were inconsistent (68). According to the government's 'Environmental Improvement Plan' (69) and regarding the air quality in homes, the government is committed to "continue to tackle domestic emissions by reducing the maximum emissions for domestic burning appliances in Smoke Control Areas and by promoting best practice in use of stoves and fireplaces". UKHSA is working to develop further the health evidence associated with exposure to solid fuel burning.

CO_2 is an indicator for ventilation. However, there has been research on whether exposures to low level concentrations (below 5,000 parts per million (ppm)) found in indoor environments may cause neurological effects such as reduced cognitive performance. A recent review found conflicting evidence due to inadequate study designs (70). Existing health impacts can be indicative of inadequate ventilation, and presence of human bio-effluents and indoor air pollutants.

Radon is the largest single source of human exposure to ionising radiation for the UK population. Radon is ubiquitous but highly variable, with doses (an exposure for a duration, multiplied by a conversion factor) ranging over 5 orders of magnitude. For the average UK resident, radon contributes as much dose as from all other radiation sources combined (71). However, a small fraction of the population will receive annual doses from radon similar to those associated with the worst nuclear events. The great majority of the UK population are currently getting modest radon doses (average of 1.3mSv per year). In more than 150,000 homes, the occupants are receiving more than 10mSv per year. In approximately 1,500 homes, the occupants are getting more than 100mSv per year, which is the order of magnitude of Chernobyl clean-up workers and would prompt evacuation after a nuclear or radiological event (Fukushima residents were evacuated at 20mSv). But as a chronic, committed dose, the effects are not immediately apparent; lung cancer risk is increased with a latency period of more than 15 years, as demonstrated in case control studies (72).

The most highly exposed individuals are at greatly increased risk of developing lung cancer, especially if they are current or former tobacco smokers (73). The lung cancer risk to all residents is proportional to the dose from radon received over a lifetime, combined with their tobacco smoking history. Radon is estimated to be responsible for at least 1,100 deaths in the UK each year (74). The lung cancer risk from radon gas itself is small, as it is usually exhaled before it can radioactively decay in the lungs. The exposure is primarily from the radioactive species created from radon decay: polonium, bismuth and lead. Changes in construction to reduce energy (through increased airtightness, window upgrades and purge ventilation, that decrease particulate matter) may reduce ventilation, leading to an increased exposure to radon, whereas unbalanced ventilation is equally bad (75).

The health effects associated with indoor biological contaminants such as fungi, bacteria and HDM, and their by-products (fungal spores, mycotoxins, endotoxins, proteolytic enzymes) can give rise to allergenic, toxic or inflammatory responses in human beings, as well as infections. Bio-contaminants primarily cause or exacerbate symptoms of lower and upper airway diseases by inducing immediate hypersensitivity (IgE) reactions, other types of immunologic responses, or infection (76). Besides respiratory problems, other health outcomes could include atopic eczema for HDM (77), whereas for fungi, a variety of non-specific symptoms have been reported, including fatigue and headaches, although the evidence for these, as well for links to cancer, is inconclusive (78).

Various studies have found associations between respiratory health outcomes and markers of dampness or moisture in buildings such as visible mould, mould odour, or moisture in the walls (for example (79)). However, further research is needed on the specific causal mechanisms for these findings (80), with a lack of health-related thresholds for moisture in buildings (81).

Overall, those most at risk from biological contaminants in indoor air are children (including prenatal exposures), people with pre-existing conditions affecting the respiratory or immune systems, with some evidence that gene-environment interactions may modulate health effects and therefore some environmental interventions may be more effective for some people or settings compared to others. Quantification of the likely health risks arising from the impact of climatic changes on biological contaminants is challenging, since some of the underlying mechanisms are not fully understood, nor are there established health-based thresholds.

3.3. Interventions for indoor air quality

Interventions are used to prevent emissions or remove indoor air pollutants. The hierarchy is first to control the emission sources and then to apply ventilation to maintain good IAQ (23). According to Nazaroff, the "12 words to improve IAQ are: minimise indoor emissions; keep it dry (relative humidity: 40% to 60%); ventilate well; and protect against outdoor pollution" (42). Changes to the hygrothermal properties of building fabric can cause condensation, mould growth and decay. The majority of adverse health effects caused by relative humidity would be minimised by maintaining indoor levels between 40% and 60%, which is the best range for healthy work performance (82, 83). This may require mechanical intervention to humidify or dehumidify the air.

There is on-going research on source control and ventilation, aiming to improve IAQ, as discussed below.

3.3.1 Ventilation

The effectiveness of ventilation in removing various types of pollutants is demonstrable (84, 85). Wargocki reported that ventilation rates below 0.4 air changes per hour (ach) are detrimental to health but identified difficulties in demonstrating causality (86). The EU-funded HealthVent project recommended a health-based airflow rate of 4 litres per second per person (l/s/p), if the indoor sources are eliminated and the World Health Organization (WHO) IAQ guidelines are met, but it would only remove emissions from the presence of occupants (exhalation) (87). A randomised clinical trial to install mechanical ventilation to improve ventilation by removing pollutants and controlling moisture found wheezing decreased in children (88). There are certainly benefits by increasing ventilation rates, but there are also potential energy penalties. Whilst a Dutch study found that mechanical systems with heat recovery can provide increased ventilation rates and improve heat recovery, there are also unintended consequences such as noise from the system, which may be an annoyance or result in the system being turned off (89). During the COVID-19 pandemic, poor ventilation was identified as a risk for far-field virus transmission and improving ventilation was identified as mitigating measure (90).

3.3.2 Active air cleaning technologies

Methods of air cleaning include carbon filters for O_3 removal (91); clean-air heat pump (CAHP) system for NH_3 removal (92); air cleaners for pollen reduction (93), for VOCs removal (94), HCHO removal (95) and PM removal (96 to 103); activated carbon filtration in the HVAC system for O_3 (91), photocatalytic cleaners (104 to 108) for PM and VOC reduction. Filters reduce $PM_{2.5}$ concentrations and are consequently expected to improve health (109 to 111) but aetiology is often unclear. Vulnerable population groups may benefit most from air cleaning (112 to 114), and these systems are predicted to improve population health when used in homes (115, 116) and schools (116), giving cost benefits (117, 118). Evidence for the effectiveness of some technologies is limited in some cases and may generate secondary chemical products (111). Gas-phase cleaners, for example, can create secondary contaminants (119) and there is no accepted standard for testing and operating air cleaning devices, which would be required for wider statutory adoption.

3.3.3 Plants

Some studies show that potted plants are effective in removing PM (120) and VOCs (121), but our understanding is immature (122), whereas other studies find no improvement in IAQ (123). All remove CO_2 to some extent, which is problematic when used to indicate ventilation rates (124, 125). The ability of house plants to clean air is dependent on species, root area, soil type, and foliage surface area. There is no standard procedure for quantifying contaminant removal rates by indoor house plants.

3.3.4 Passive removal materials (PRMs)

Passive removal materials (PRMs) refer to wall materials and coatings. The high reactivity of O_3 and its interactivity with room surfaces makes PRMs a viable removal mechanism. The most promising PRM materials are clay bricks, plasters, calcareous stones, mineral fibre or volcanic perlite tiles and sealants. The cTrap cloth is a sealant, an emission barrier that contains 2 active layers; one adsorption layer and one hydrophilic polymer layer, which when attached to indoor surfaces can effectively reduce emissions of a range of VOCs (for example, alcohols, aldehydes, sulphur compounds, polycyclic aromatic hydrocarbons (PAH), chloroanisoles, chlorophenols) (126 to 128). However, HCHO is a problematic bi-product (129). Hempcrete, a concrete-like building material with a hemp base, naturally regulates moisture and temperature more efficiently than concrete (130). Heating dissipates stored contaminants (131). Technologies are immature and performance and implementation regulation is needed.

3.3.5 Behavioural interventions

As the climate changes and while solutions are proposed for control of emission sources and provision of adequate ventilation, an integrated approach to improve IAQ and occupants health and wellbeing needs to be considered; this takes into account not only the role of building designers, managers and owners but also the role of occupants (28, 132, 133). Behavioural interventions to improve IAQ are analytically reported in the literature (23, 25, 28, 134, 135) and summarised here.

Indoor air quality can be improved by changing certain occupant behaviours or habits; by refraining from smoking and vaping indoors, and from using solid-fuel fires or free-standing gas heaters where possible or using these with increased ventilation. The latter is also required to remove additional moisture generated from normal occupant activities, such as drying clothes indoors, cooking, having a shower or bathing, which lead to damp and mould issues. Release of chemicals can be reduced by reading and following guidance on how to use cleaning and personal care products and by using low emission materials for decorations and furnishings (for example, paints, furniture and flooring materials), where, and if, possible.

Efficient measures to remove indoor air pollutants and moisture include the use of provided background ventilation (most commonly trickle vents), externally extracting mechanical fans in the kitchen and bathroom, which are operated during the activity, as well as windows opening, where appropriate due to outdoor air pollution and if is safe, due to security issues. The maintenance of mechanical systems, by regularly cleaning or replacing filters, can ensure their effectiveness. Where ventilation is restricted, using portable air cleaning systems, such as fans with HEPA filters or UVC systems can reduce particulate pollution.

4. Climate change, building overheating and health outcomes

4.1 Determinants of exposure

Below is a review of some of the factors driving indoor overheating risks in buildings.

4.1.1 Building location and the surrounding microclimate

Across the UK, the magnitude of overheating risk varies, with London and the South of England being at highest risk (11, 136). Several studies have indicated that homes in colder regions experience indoor overheating even under the current climate (11, 137, 138). Urban dwellings are generally more prone to overheating due to the urban heat island (UHI) effect, a well-established phenomenon whereby central urban areas can be around 4°C to 5°C warmer than their outskirts, with the difference exceeding 10°C in some cases (139). Excess heat-related mortality has been higher in London compared to other UK regions during heatwaves (140, 141). Importantly, dwelling types that are more likely to overheat due to their building characteristics, such as flats, are often located in the warmer parts of a city, further exacerbating their overheating risk (142, 143).

Location of a dwelling unit or room within a building can also affect overheating risk (144, 145). Purpose built flats, in particular top floor flats, are commonly identified as more prone to overheating compared to flats at lower floors (146 to 149). Smaller flats are also less likely to offer a 'safe haven' during periods of hot weather, that is, a room that remains cooler for parts of the day (143, 150). Overheating appears to be more prevalent in bedrooms during the night, rather than in living rooms during the daytime (151, 152), although this varies by dwelling type and construction age (153).

4.1.2 Building geometry

Building geometry, including building size, form, massing, orientation, layout, proportion of transparent elements and shading can affect the level of exposure of the building fabric to solar radiation and resulting solar gains (145). These factors will also affect the potential for convective heat losses through the building fabric. Heat loss occurs primarily through opening windows, which is currently the main cooling strategy in UK dwellings. Apart from shading, and to a certain degree interior layout, elements of building geometry are largely determined by early-design stage decisions, highlighting the importance of early-stage design for overheating prevention. Smaller, purpose-built flats and terraced houses are more likely to overheat than detached houses (142, 143, 147, 150, 154). New builds commonly feature large, glazed areas prone to overheating, especially if unshaded or south or west facing (155). However, there are also numerous dwellings prone to overheating, particularly urban flats, due to minimal window openings or difficulty leaving open securely at night (156).

4.1.3 Building thermal characteristics

Thermal characteristics of buildings, including thermal reflectivity (albedo), absorptivity, insulation, air permeability, and thermal mass, can modify both heat gains and losses in buildings. For instance, low albedo is associated with high indoor temperatures due to increased solar heat gain absorption (155, 157 to 161). Thermally lightweight structures are found to overheat more quickly during the day (155, 162, 163). Buildings with higher thermal mass have been found to lead to more stable indoor temperatures, though this should also be coupled with appropriate ventilation so that any build-up of heat indoors can be effectively removed.

Achieving high energy efficiency through increased thermal insulation and air permeability is crucial to reduce winter carbon emissions associated with space heating. However, thermal efficiency features, typically associated with more recently constructed dwellings, have been identified as potentially contributing to summertime overheating risk (5, 138, 151, 162, 164 to 167). Crucially, this is mainly due the absence of appropriate ventilation, shading or other passive cooling strategies (147, 156, 159, 167 to 171). Wall insulation positioning can also be important, with internally positioned insulation leading to higher overheating than externally placed insulation (147, 172, 173).

4.1.4 Internal heat gains

At the household level, metabolic heat gains can be generated by occupants and other internal sources related to occupant behaviour, such as lighting, cooking, and use of appliances. In blocks of flats, significant internal heat gains have been observed in corridors and other communal areas as the result of waste heat from domestic hot water distribution or communal heating systems (156, 174).

4.1.5 Household socioeconomic profile

Social housing tenants, lower income households and vulnerable individuals (older, disabled or suffering from long term illnesses) are often found to experience higher overheating risks compared to other tenure types or the rest of the population (143, 153, 175). It is likely, however, that these factors are correlated with other overheating determinants, such as dwelling type, location or limited thermal adaptive capacity.

4.2 Health impacts

The epidemiological relationship between excess or prolonged heat exposure and adverse health and wellbeing effects is well established (176 to 179). These impacts include a range of symptoms, such as heat cramps, heat exhaustion, heatstroke, hyperthermia and even death and suicide risk (180, 181). Certain sociodemographic groups are expected to be more severely affected, including older, very young, immunocompromised and individuals with physical or mental health conditions (8, 180, 182). People suffering from cardiovascular, respiratory, cerebrovascular and diabetes-related disease are particularly at risk (181). People with low mobility or who are bed-ridden may be particularly at risk due to their limited ability to adjust their environment during hot spells (175), while living alone at home has also been identified as a heat vulnerability factor in some studies (177).

Although more research is required to understand the impacts of indoor heat exposure in UK homes on health and wellbeing (183), a recent systematic review of international literature has identified worsening of respiratory, dementia and schizophrenia symptoms when indoor temperatures were above 26°C (184). Indoor overheating can negatively impact sleep quality, with subsequent adverse effects on wellbeing, productivity and risk of accidents, and it has been suggested that elevated night-time bedroom temperatures can contribute to heat-related morbidity and mortality (183, 185).

4.3 Interventions for building overheating

As indoor overheating is projected to become more frequent in the UK, adaptations are needed to mitigate risks to health (5, 11, 183, 185 to 187).

At the country-, city-, and neighbourhood-level, adaptative measures can include heatwave planning and response (188), public education campaigns (189) and the creation and improvement of green and blue infrastructure, such as trees, parks, ponds, green roofs and walls (160, 162, 189 to 192). More details on adaptive measures for outdoor environments can be found in Chapter 4.

At the building-level, it is crucial to consider indoor overheating mitigation at both the design and refurbishment stage to prevent lock-in design decisions that may result in high summer temperatures (148, 193). While retrofitting the existing housing stock may increase building energy efficiency, and thus decrease winter heating demand, either active or passive cooling strategies should be implemented to avoid extreme risk of overheating (165). Air conditioning (systems that manipulate the moisture content of supplied air, AC), comfort cooling (systems that only manipulates temperature of supplied air), mechanical fans, and heat pumps, are all considered active cooling, which rely on external energy supply for heat transfer. In the UK, between 2% to 5% of homes are currently estimated to have some form of portable or fixed cooling system (194) although this may increase in future warmer years, especially following the record-breaking outdoor temperatures in summer 2022 (189, 194, 195). While AC can help manage indoor temperatures during periods of warm weather, it further contributes to a warming climate by consuming energy, especially if non-renewable energy sources are used, and can put extra strain on the electrical grid (195). Its use may also impose an economic burden on households and exacerbate summertime fuel poverty (5). Furthermore, running a typical standard AC unit (without heat recovery) can contribute to the UHI effect through the release of waste heat outside of dwellings, potentially increasing overheating risk for nearby households (177, 189, 196).

Passive cooling measures can protect, modulate, and dissipate heat with minimal energy consumption (194, 197). The new approved Building Regulations for overheating mitigation (Approved Document O) specify that passive measures should be prioritized over mechanical systems (15). The suitability of passive cooling strategies will depend on many factors, including geography and climate, building geometry and thermal characteristics, as well as occupant needs and behaviours (145, 197).

Natural ventilative cooling is effective in the UK, due to a sufficient diurnal temperature difference for night ventilation to have a cooling effect (194). However, its effectiveness will likely decrease as the climate warms (168, 196, 198). A gap is often observed between ventilation design intentions and occupant ventilation behaviour resulting in increased overheating (8, 199), highlighting the importance of education around the use of passive cooling strategies in a warming climate (155, 189, 198, 200). Hybrid solutions, with passive and active measures working synergistically may be needed in the future (201).

External shading (such as external shutters, window overhangs and brise-soleil) have been shown to reduce overheating and associated heat-related mortality under current and future climate scenarios (145, 148, 154, 165, 167, 172, 198, 202 to 204). It is estimated that if the West Midlands dwelling stock was adapted with external shutters, which were closed during daytime, heat-related mortality could decrease by 60% in current summer conditions, 30% during current heatwave conditions, and 37% to 43% in weather conditions representative of 2030s, 2050s and 2080s summers within the A1B future climate scenario (154). However, the technical feasibility of external shading may be limited in the UK, as many existing dwellings have windows that open outwards (5, 143). Internal shading, such as blinds, can reduce internal temperatures at a lower cost but have been found to be less effective than external systems because solar gains have already been transmitted through the glazing (155, 172, 194, 205).

Green roofs and façades can reduce cooling demand, stabilize indoor temperatures, and reduce the UHI effect. They do this by providing an additional layer of building insulation and shading, and through evaporative cooling, absorption and reflection of solar radiation (167, 192, 194, 206 to 209). Effective integration of green roofs in the UK would need to consider local climate, building infrastructure, and maintenance needs and costs when selecting substrate, plant species, and their design (such as extensive (shallow soil systems) versus intensive (deep soil systems)).

Reflective coatings applied to roofs and façades (that is, white or super cool coatings) can also reduce indoor temperatures, cooling demand (154, 157, 158, 161, 198), and the UHI effect (210, 211) by reflecting solar radiation away from the dwelling. However, a consideration for colder climates, such as the UK, are the impacts of reflecting solar radiation year-round, including desirable heat in the winter (5, 154, 157).

At the individual-level, people can adapt to overheating behaviourally, through adjusting clothing or window opening, or physiological changes, sweating and metabolism (200). How people occupy and operate in a space can impact the effectiveness of other building- or city-level interventions, which is further influenced by surrounding environmental, social, and demographic factors and knowledge and awareness of precautionary measures (177). For example, window opening behaviours are influenced by indoor and outdoor temperatures, perceived security (relevant for ground level apartments), safety (such as window restrictors to reduce fall risks), as well as environmental conditions such as outdoor air and noise pollution (147, 169, 212, 213). Furthermore, having reduced mobility can limit people's ability to adjust their immediate environment (such as opening windows), clothing, and activity levels (170). Whether people install and use adaptive measures is also influenced by cost, preparedness and knowledge of those systems (199, 214).

In summary, a combination of adaptation measures is required to minimise the risk of indoor overheating in UK residential settings. Given the complexity of the problem, a holistic approach to designing and retrofitting dwellings is required. This approach should consider the cooling energy burden of active measures; installation costs, planning restrictions, feasibility and effectiveness of passive measures; and occupant behaviours and needs, whilst ensuring that other environmental conditions are not compromised.

5. Climate change, noise and health outcomes

5.1 Determinants of exposure

Whilst some sounds can promote good health and improved quality of life (215), noise is unwanted or harmful sound (216). Noise exposure indoors can be due to indoor sources or from the ingress of noise from outdoors or adjacent buildings. Here, indoor sources of noise refer primarily to mechanical systems that are required for a safe and healthy indoor environment, such as ventilation, heating and cooling systems. Outdoor sources of noise include transport, external building services, construction, and industry.

A building's siting, orientation, façade construction and ventilation strategy play a significant role in determining occupants' exposure to noise from external and internal sources. The need for ventilation can be at odds with reducing exposure to noise and may influence ventilation behaviours. Occupants may be reluctant to open windows and doors to ventilate dwellings in noisy environments, which can impact indoor overheating and air quality (169, 213, 217, 218). This conflict may also worsen over time as the need for ventilative cooling increases with a warming climate. Mechanical service systems are designed to regulate indoor temperatures and improve air quality but if not designed, installed and maintained properly, they can be sources of noise (219 to 224). Indoor noise generated by mechanical ventilation units may be particularly noticeable in situations where there is low background noise, such as in a modern dwelling with a well-sealed façade, or particular times of the day (225). There is some limited evidence from the UK that noise from mechanical ventilation units can reduce indoor perceived acoustic comfort (226), and can affect their use, such as occupants turning the units off or lowering the operating level (199, 227). However, there is still a lack of good quality evidence on the exposure levels and sound characteristics of mechanical ventilation noise that occupants may find acceptable in the UK (225).

5.2 Health impacts

Exposure to environmental noise has well-established detrimental impacts on psychological and physiological human health, such as sleep disturbance and cardiovascular diseases (228). The etiological pathways might be the repeated stimulation of the sympathetic nervous system, hormonal imbalances, and noise-induced sleep fragmentation (229, 230). The WHO has set guidelines for the European Region to limit health impacts from exposure to transport (road, railway and aircraft) and wind turbine noise. Since the publication of the WHO guidelines (228), the evidence for adverse health impacts due to noise has continued to grow rapidly, particularly for cognitive impacts and cardiometabolic diseases (231 to 237), including for sources other than transport, such as neighbour noise (238 to 241). Most epidemiological evidence is in relation to long-term averaged sound levels predicted or measured outside the façade of a dwelling. However, emerging evidence suggests that observed associations between noise and health outcomes are more robust when linked to indoor exposure (242).

The health impacts of exposure to mechanical ventilation noise is still a poorly understood problem, especially as annoyance and sleep disturbance are likely to be influenced by not just time-averaged levels, but also sound quality (243 to 245).

Inequality and inequity in health impact can arise from several factors, including exposure disparities, vulnerability and affordability. The limited evidence available suggests that the relationship between environmental noise exposure and socio-economic status in England is complex, varying by source of noise (246) and region (247). Vulnerability to environmental noise exposure can arise from social, environmental or biological determinants, or the combination of the 3 determinants (248).

5.3 Interventions for noise

Climate change mitigation and adaptation policies are likely to lead to changes in building design and refurbishment that can have both a positive impact as well as unintended consequences on indoor sound exposure. These impacts may arise because of changes to the building fabric, which provides a degree of protection from external noise sources, as well as from new sources of internal and external sound.

Properly designed and installed thermal insulation measures may also improve the acoustic insulation performance of the building fabric (windows and walls, including through improvements of airtightness), which can further improve acoustic insulation to outside traffic and neighbour noise (249 to 253). However, there is still limited evidence on the effectiveness of insulated windows and walls for improving subjective responses of indoor acoustic comfort and reducing annoyance from environmental noise, particularly from a UK context (254). Interventions that increase airtightness should not inadvertently worsen indoor air quality or increase the risk of overheating, and solutions that include mechanical ventilation or cooling should factor in noise emissions in the design, installation and maintenance of such systems (225). Considerations should also be given to the lifecycle carbon and environmental cost of thermal and acoustic insulation materials (255 to 257).

Sound attenuating modifications can be applied to the building envelope to help address the competing needs for ventilation, cooling, and quiet. These include modifications to balconies (253, 258 to 261), eaves or louvres (262), solar shading infrastructure (262 to 265), external shutters (266), and vents (267, 268). Special windows have been developed that allow for natural ventilation while also attenuating outdoor noise ingress (259 to 261, 269 to 274). However, more research is needed to demonstrate their acoustic and ventilative performance in a UK context.

Green roofs and façades can improve the indoor sound environment through external noise reduction (275 to 278). Building envelopes are typically acoustically hard, and as a result, sound is reflected and then amplified between nearby buildings and street surfaces (277 to 279). If designed properly, green roofs and façades can reduce indoor noise exposure by lowering the acoustic intensity incident on façades from outdoor sources (280 to 284). The acoustic attenuation performance depends upon many factors, including substrate material, moisture content and vegetation type. Green roofs and façades can make desirable sounds, such as nature-based sounds, more noticeable (280), can decrease the perceived loudness of traffic noise (279) and reduce noise annoyance (285, 286).

6. Flood and water damage and IAQ

6.1 Determinants of exposure

The risk of flooding to people, communities and buildings is one of the most severe risks from climate hazards for the UK population, both now and in the future (5). There are now known to be just under 1.9 million people in the UK exposed to frequent flooding from either fluvial, coastal or surface water flooding. Approximately 82% of those at risk are in England, 8% in Wales, 8% in Scotland and 2% in Northern Ireland (287). Flooding is expected to increase significantly across the UK as climate change leads to more frequent heavy rainfall, especially in winter, due to the warming of the atmosphere which leads to more water vapour content and hence more precipitation. Increases in both fluvial (river) and pluvial (surface water) flooding will occur as well as more coastal flooding due to rising sea levels from increasing temperatures and melting land ice.

Moisture damage of buildings arising from extreme weather events such as flooding and hurricanes can increase dampness in buildings and associated biological contaminants such as fungi and bacteria; post-hurricane clean-up and reconstruction exposures can increase the risk for lower respiratory symptoms (288). As such, wearing protective equipment during clean-up activities can be important, particularly for immunosuppressed residents (289). Increased occurrence and severity of driving rain can increase the risk of moisture damage and associated biological contamination in buildings, depending on the construction details of the building's fabric (290, 291).

6.2 Health impacts of floods

The health impacts as a result of indoor flooding were summarised previously (4), and are covered in more detail in Chapter 3. They include CO poisoning occurring after flooding, when generators or fuel-powered equipment are used indoors for drying or pumping out flood. The persistence of flood-borne microorganisms on building surfaces, depending on the level of sewage contamination of the water and the drying rate of the surface, and the food and water contamination by bacteria, sewage, agricultural waste or chemicals during flooding events lead to infection risk. Mould species, such as *Cladosporium*, *Aspergillus*, *Penicillium*, *Alternaria*, and *Stachybotrys* species of fungi have all been observed in flooded dwellings, whereas damp indoor environments have been associated with respiratory health problems. Most health impacts in England are associated with mental health such as psychological distress, probable anxiety, probable depression and probable post-traumatic stress disorder.

6.3 Interventions for flooding

Considerable advances have been made regarding the strategic management of flood risk at national and local levels in recent years, including the promotion of a shift from physical protection to adaptation and resilience (5). Since April 2016, insurance has been made available for all properties that have been flooded in the past, with nearly half a million households now covered (292). The company has supported the concept ‘Build Back Better’ to ensure that further floods have much less impact. Flood Re are also supporting the idea of flood performance certificates being issued to properties liable for flooding to act as an incentive for owners to take preventative measures, as well as alerting prospective buyers to the state of preparedness (293).

7. Lighting

7.1 Determinants of exposure

Daylight consists of light at wavelengths across the visible spectrum and beyond. It has many advantages over electric light: it is free, ubiquitous, abundant, well-timed (most of the year) and practically flicker-free. Whilst direct sunlight can cause glare, indirect natural light through windows does not. Daylight also provides higher levels of illumination near windows than can be economically created with electric lighting and requires no direct electrical energy input. Windows and glass doors are the most common means of admitting daylight into homes, whilst selectively blocking short wavelength ultra-violet light. Infra-red filters can now be used to block 2-way radiative heat transfer through window glass.

7.2 Health impacts

Over the last 25 years, it has been increasingly recognised that illumination for vision has a different spectral requirement to the light that is essential for human health. In particular, there is established evidence of the effects of light on the timing and health of circadian rhythms – as light can either be to maintain or disrupt circadian function, depending on timing, intensity and several other factors – and on sleep and long-term health, for example (294 to 300).

Evidence relating to other photobiological effects of daylight is emerging, such as its role in reducing myopia in children, and on blood pressure. Although there is no consensus on lighting for these effects, it is often suggested that there are benefits from higher illumination during the day. In addition, with age the lens becomes gradually less transparent and there is also an increase in visual impairments; both age and visual impairment may further increase the need for better lighting (301).

To summarise, the health aspects of lighting call for day-occupied spaces with adequate daylighting, possibly different characteristics of artificial lighting for daytime, evening and night use, controls over direct sunlight, and the means to remove any unwanted light in the evenings and night. Many people also benefit from the natural prompt of the morning daylight, so passive black-out solutions may present barriers to healthy morning exposures.

There is a current lack of requirements for lighting and health in the design of homes, but experts recently agreed recommendations for adult exposures (302, 303). As a brief summary, lighting should be brighter and closer to a daylight spectrum during the day ('bluer') – including the contribution of daylight – but dimmer and warmer ('redder') in the evening before bed, with darkness whenever possible overnight. Following these health recommendations will potentially have significant implications for energy use of buildings and the assessments of energy efficiency, including where electrical lighting needs to be increased during the day or increased in the evening, and where increasing daylighting changes the thermal properties of the design.

As a result, there is a risk that projected reductions in power consumption from lighting may not be fully realised.

7.3 Interventions for lighting

A spectral weighting function, allowing only for visibility or visual brightness, is used to calculate light output from electrical lighting, and energy efficiency is then obtained by dividing by the power consumed. But lighting should have a balance of wavelengths to achieve an acceptable colour and for colour rendering quality, which has cost implications on energy efficiency. Although the highest efficacy might be assigned to a green wavelength, a strongly coloured green light will not be acceptable, and so maximum energy efficiency is not feasible in practice.

In addition, the lighting energy efficiency assessments outlined above rely almost exclusively on luminous energy efficiency, that is, visual brightness, whereas light has several beneficial and detrimental health effects with other spectral dependencies. As energy-efficiency performance, and get nearer to the maximum, using this narrow definition of efficiency is increasingly inconsistent with achieving healthy daily variations in the light environments indoors (303).

A further result of higher energy efficiency targets is an increase in the adoption of light-emitting diode (LED) lighting. When operated or dimmed with unsuitable drivers and dimmers, LEDs may flicker or produce temporal light modulation, and this could cause headaches, reduce visual performance and even results in safety risks with rotating machinery (304). Nevertheless, LED technology has advantages in spectral tuning, which may help achieving many of the health targets already discussed.

8. Impact of energy efficiency in homes on indoor environmental quality and health

8.1 Impact of energy efficiency measures on IEQ

Using low-carbon technologies for heating and cooling, energy-efficient lighting and exploiting solar energy will help existing UK homes to become low carbon and energy efficient, tackling simultaneously winter fuel poverty, improving thermal comfort in winter months, and reducing mould. However, energy efficiency measures may be also associated with several unintended negative consequences if poorly installed, especially with respect to IEQ (Section 7.3; (305, 306)).

MVHR systems, which were installed in homes that underwent fabric retrofit, were proven to reduce energy consumption, reduce damp and mould by reducing relative humidity, and improve thermal comfort, as shown by monitoring (307) and modelling studies (147). Formaldehyde and other VOCs were found to be high during specific retrofit works (plastering, painting), whereas post-retrofit, these levels dropped significantly (307).

However, shortcomings using MVHR systems were also reported, which are associated with “inadequate specification, incorrect commissioning, poor installation and performance, lack of maintenance, thermal comfort complaints, noise, occupant interference and a lack of knowledge and awareness of the systems” (308). In a study on the performance of the MVHR systems, only 16% of systems were commissioned correctly, and only 56% of installations met the design air flow value. The role of occupants is also of important, with research highlighting a preference for natural ventilation, high prevalence of air polluting activities and inadequate perception of IAQ (308). IAQ monitoring campaigns and occupant interviews identified presence of fungal growth, high levels of relative humidity (more than 60%), significant variance in heating patterns, occurrence of sick building syndrome symptoms and issues with the MVHR system (309). Inadequate filtration with the MVHR and openable windows, even during the heating season, led to high HCHO and PM levels, suggesting indoor sources of these and other pollutants other than the retrofitting activities (307). CO_2 levels were high when the trickle vents were closed or when the MVHR system was not working properly or turned off completely (21, 309). A post-occupancy study on new-build dwellings at 6 sites in England and Wales in 2015 found that nearly all of the 13 occupants interviewed had turned off their ventilation systems, finding them too noisy, especially at night (227).

Proper installation which follows best practice (such as PAS 2035) should mitigate the impacts of poor installation and unintended outcomes of energy efficiency measures. Rigour and best practice in energy efficiency retrofits needs to be promoted.

Heat pumps installed in naturally ventilated flats led to lower concentrations of indoor air pollutants and CO_2, due to increased ventilation, resulting from very frequent window opening;

heating was typically always on and cheaper to run than before the installation of the heat pumps (310). However, in homes with limited window openings and presence of indoor sources, VOCs, HCHO and PM levels were high, indicating the need for integrating continuous background ventilation that could be demand controlled (310).

It is worth mentioning that, despite the above issues, homes with MVHRs and heat pumps are very much in the minority. Data on air tightness and ventilation in real buildings is quite poor and unrepresentative, which is linked to the lack of monitoring data on IAQ; modelling studies aim to cover this gap and improve our understanding.

IAQ was modelled assuming housing energy efficiency retrofits, under different ventilation scenarios (311). Fabric and heating retrofits that were carried out together with the addition of ventilation systems reduced indoor sources of pollutants ($PM_{2.5}$, radon, and mould), but increased indoor exposure to outdoor-generated $PM_{2.5}$. In the case of inadequate ventilation and noticeable mould, energy efficiency measures did not have a wide benefit, reducing ingress of outdoor air but leading to increased indoor air pollutant levels. Finally, if there was no additional ventilation, the average indoor pollutant concentrations were further elevated compared to the previous scenario. Similar results were reported where CO levels exceeded recommended exposure levels in kitchens following retrofit without additional ventilation (34).

Climate change mitigation measures are likely to affect indoor radon levels. These will be from a combination of rising temperatures and extreme weather (especially wind), energy efficiency measures such as building insulation, and window management including the installation of metal shutters that reflect sunlight but allow fresh air exchange. However, some adaptations could counter the radonogenic effect of others. Increased building insulation means that indoor temperatures remain high during the winter with a corresponding increase in radon level, especially if outside air ingress is restricted, which has been shown by comparing the radon levels in UK homes before and after the installation of energy efficiency measures (312). Some climate change mitigations increase indoor radon levels, making previously modest doses become more significant at a population level. For example, the average UK radon level is $20Bq/m^3$, but after fitting triple-glazing, it can increase to $100Bq/m^3$. It should be noted that lung cancer risk from radon increases 16% for every $100Bq/m^3$ increase (72). Radon levels in underground spaces, such as basements and cellars that maintain a cool but stable temperature year-round, can show the opposite seasonality (as well as an overall increased radon level). This should be considered as people ‘build down’ to take advantage of the temperature-stabilising effects of the ground.

The potential impact of energy efficiency measures on biological contamination in buildings can be complex, as measures could lead to generally warmer indoor environments and higher absolute humidity (due to reduced air exchange), thus potentially creating more favourable conditions for fungi, HDM and potentially some bacteria. For example, an observational study of social housing in Cornwall (UK) found an association between higher energy efficiency ratings and current asthma in adults, with higher energy efficiency also associated with visible mould and mouldy or musty odour (313). On the other hand, relative humidity levels could be lower due to higher temperatures, and there might be a reduction in cold surfaces (as well as reduced condensation risk) if the fabric is well insulated.

When energy-efficient retrofits occur, summertime ventilation will need to be increased in UK homes to reduce overheating risks, which will lead to greater exposure to pollution from outdoor sources and reduced exposure to pollution from indoor sources (147). Uncontrolled ventilation through trickle vents may lead to heat loss and the ingress of unfiltered outdoor air and a shift from passive, occupant controlled natural ventilation to natural ventilation in conjunction with automated active ventilation systems is recommended (147).

Following a fabric retrofit in social housing (6 cases), summer temperatures ranged between 21°C and 26°C in most cases, with one exception where summer temperatures often exceeded 27°C and reached 29°C at times (21). Internal relative humidity levels were also affected, which in general were quite low; less than 60% in the non-heating season (May to September) in most cases (21).

8.2 Impact of energy efficiency measures on health

In the UK, an increased number of lower income households are receiving fabric insulation and new heating systems to reduce energy use and fuel consumption. These interventions have the potential to reduce the risk of cold-related illnesses by making homes more affordable to heat and improve both physical (respiratory and asthma) and mental health (9, 314).

The impact of household energy efficiency on asthma in social housing was previously assessed (313). A unit increase in household SAP rating was associated with a 2% increased risk of current asthma, with the greatest risk in homes with SAP greater than 71. In a follow up study, the association between energy efficiency interventions and health was assessed over a 3-year period (315). Although loft insulation interventions were positively associated with a significant increase in admission rates for COPD and cardiovascular disease (CVD), higher levels of boiler and glazing replacement were associated with slightly lower admission rates for COPD and CVD, as a result of increased warmth.

When additional ventilation was not provided together with the dwelling energy efficiency retrofits, despite the reduced ingress of outdoor air pollutants, there was an increase in air pollutant concentrations, with a net negative impact on health (311). This study estimated that adequate ventilation could improve home energy efficiency and lead to 2,200 quality adjusted life years (QALYs) gained per 10,000 people in England over 50 years (311).

Focusing on PM, one study simulated the impact of emission reduction strategies (building fabric improvements, improved ventilation, fuel switching, and occupant behaviour changes), aiming to reduce annual average $PM_{2.5}$ indoor concentrations by 3.0µg/m^3 by 2050, compared with the 2010 baseline (316). This intervention would result in an increase of just over 13 million QALYs over the modelled 90-year follow-up period. There would also be an average increase in quality-adjusted life expectancy at birth of 101 and 68 days for males and females, respectively (316). Benefits of the intervention for mortality would generally increase with age, with a peak at around age 80; over 300 fewer deaths in the population per year at this age by the end of the follow-up period were estimated (316).

9. Conclusions and priorities

9.1 Research priorities

There is a need for systematic surveillance of IAQ and health in homes and other buildings. Large monitoring campaigns were carried out by the Building Research Establishment in 1,000 homes more than 20 years ago to characterise the indoor environmental quality in UK homes (317). Since then, there have been small scale studies, some of them funded by the government to provide an insight on ventilation, indoor air quality and physical parameters in new homes, built under the latest building regulations, just before their revision. As a result, the indoor environment has not been recently well characterised across the UK. Carrying out systematic monitoring of the indoor air, in the same way that outdoor air is monitored, would capture the effect of changes made to the housing stock on IAQ, maximising the benefits of energy efficiency measures and minimising the unintended health consequences (318). IEQ monitoring should be sufficient to demonstrate the impact of weather conditions, their seasonal and diurnal variations on ventilation practices as well as the impact of occupant activities on ventilation and IEQ. Projects have been recently funded under the UKRI Strategic Priorities fund Clean Air Programme; however, the momentum needs to be maintained beyond the end of this programme.

Interdisciplinary behavioural science and citizen science studies are required to demonstrate the interactions between energy efficiency measures and occupants' behaviour, preferences and needs that could have an impact on their health and wellbeing. Further research is needed to evaluate the effectiveness of interventions in a holistic way, which would then lead to healthier homes and occupants.

Since current research is focussed on the impact of energy efficiency retrofitting on IEQ mainly in social housing, research is needed to evaluate the impact on private sector homes. Research could either include as a reference similar non-retrofit homes and assess the changes in IEQ and health relative to these homes or monitor the same homes before and after retrofitting. Furthermore, as more homes take-up low carbon heating (such as heat pumps), it will be useful to have more studies examining the IAQ benefits of low carbon heating (before or after).

9.2 Implications for public health

Awareness of the health and wellbeing implications of good IEQ among health care professional could be promoted. This may be achieved through bespoke guidance and training.

Healthcare professionals should be aware of the interventions that could in particular be recommended to patients with allergies and pregnant women (23). Furthermore, improvements in air filtration would protect against particles and are expected to provide health benefits.

Therefore, a multi-intervention approach that would include both medication and environmental home interventions would be effective and beneficial.

9.3 Considerations for built environment professionals

Integrated design and whole system approaches should be used when considering how to design and retrofit homes that are resilient to climate change and associated IEQ risks. The role of ventilation in modulating thermal conditions as well as air quality need to be carefully considered, whilst also addressing the potential of links with noise issues (from the residential ventilation system, or from outdoor for natural ventilation). Optimising a retrofit for winter heating, summer cooling, and IAQ is not trivial and challenging and is currently outside the scope of much guidance (Part O, PAS 2035, or industry standards), which usually focus on one criterion at a time. As such, steps could be taken to improve this.

To reduce the risks from climate change and IEQ in existing buildings, built environment professionals are encouraged to collaborate with other disciplines (such as public health) and stakeholders (for instance, local authorities) to develop actionable indicators of quality and workable warning systems. Data on health outcomes associations should be collected, to reduce risk of unintended consequences and justify cost effectiveness of intervention. Training should be provided by relevant professional bodies.

Acronyms and abbreviations

Abbreviation	Meaning
CCRA	Climate Change Risk Assessment
CO	carbon monoxide
CO_2	carbon dioxide
CVD	cardiovascular disease
GHG	greenhouse gases
HCHO	formaldehyde
HDM	house dust mites
HECC	Health Effects of Climate Change in the UK report
IAQ	indoor air quality
IEQ	indoor environmental quality
I/O	indoor/outdoor ratios
LED	light-emitting diode
MVHR	mechanical ventilation with heat recovery
NH_3	ammonia
NO_2	nitrogen dioxide
NO_3	nitrate radicals
O_3	ozone
OH	hydroxyl radicals
PHE	Public Health England
PM	particulate matter
PRM	passive removal materials
QALYs	quality adjusted life years
SAP	Standard Assessment Procedure
SOAs	secondary organic aerosols
sVOCs	semi-volatile organic compounds
UHI	urban heat island
VOCs	volatile organic compounds

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