Department for
Business, Energy
& Industrial Strategy

Heat, energy efficiency, smart technology and health

A review of evidence from high-income countries, with a focus on the UK

Results report

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Preface

RAND Europe was commissioned by the Department for Business, Energy & Industrial Strategy (BEIS) in 2019 to conduct a rapid evidence assessment on the health and wider societal impacts of poor indoor heating in the home and workplace. The rapid evidence assessment also aimed to explore the impacts on human health and the indoor environment of introducing energy efficient and smart heating systems.

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Executive summary

Background and objectives

According to recent European Union Statistics on Income and Living Conditions (EU-SILC), 6% of the population of the United Kingdom, or almost 4 million residents, are unable to keep their home adequately warm. This may be for a number of different reasons, including housing deficiencies, old and/or inefficient heating systems, and economic status, or a combination of these. Excess heat may be a problem, too, as may indoor air pollution caused by old and/or poorly maintained heating systems.

The above situation has a significant impact on public health in the UK. Living in a home that is too cold increases the incidence of a number of health-related issues and is one of the main contributing factors to excess winter deaths[1] every year. Children and the elderly, who spend proportionally more time at home, are particularly vulnerable. Additional health needs linked to the health impacts of living in a cold home lead to financial strain on health services, with an estimated cost to the National Health Service of £850 million per year.

Recent decades have seen enormous improvements in the energy efficiency of buildings and in heating technologies. These improvements are often discussed and presented in light of their benefits for the environment and for the reduction of domestic heating costs. The UK government, in its ‘Clean Growth Strategy’, has explicitly and prominently mentioned the contribution that improved homes need to make for the UK to achieve the reduction in greenhouse gas emissions outlined in the Paris Agreement. That same strategy paper also makes frequent reference to the problem of fuel poverty and sets out concrete measures to reduce the problem through energy efficiency improvements (BEIS, 2017a).

In addition to the benefits outlined above, improved energy efficiency of buildings and new heating technologies have the potential to help improve public health.

The objective of this study has been to examine these issues in detail, focusing on the following overarching research questions:

1. What is the impact of poor indoor heating on health?
2. What are the wider societal impacts of poor indoor heating?
3. What is the impact of energy efficiency improvements, renewable heating technologies and smart technology on the indoor environment?

[1] Excess winter deaths is defined as the observed total number of deaths in winter minus the average number of deaths during the rest of the year. It describes the number of additional deaths in winter months compared with summer months. More information can be found at https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/deaths/bulletins/excesswintermortalityinenglandandwales/2017to2018provisionaland2016to2017final

4. What is the impact of energy efficiency improvements, renewable heating technologies and smart technology on health?

To answer these questions, the study team carried out a rapid evidence assessment of the available academic literature and high-quality grey literature from high-income countries since 2010.

The impact of poor indoor heating on health and on wider society

The World Health Organization (WHO), Public Health England (PHE) and the National Institute for Health and Care Excellence (NICE) generally recommend indoor temperatures should fall between 18°C and 21°C. However, it is important to bear in mind that these recommendations relate to people in good health and state that those who have a higher risk of poor health from lower temperatures may need slightly higher indoor temperatures.

The prevalence of poor indoor heating in the UK is fairly high. It is strongly linked to ‘fuel poverty’, the issue where low-income households live in a home that cannot be kept warm at a reasonable cost. Certain groups are at particularly high risk of fuel poverty. These are children, the elderly, people with existing health conditions, people living in rural locations, and people living in privately rented or owned homes rather than social housing.

There is evidence that excess indoor cold is linked with higher mortality. Again, certain populations are at particularly high risk, notably the elderly. There is also evidence that poor indoor heating has a negative impact on respiratory health. This includes general respiratory health, asthma, allergic conditions, wheeze, lung cancer, infections and chronic obstructive pulmonary disease (COPD). But it should also be said that a number of studies the research team reviewed did not find significant associations with these health outcomes.

Furthermore, living in a cold home is associated with an increase in blood pressure and slower recovery from cardiovascular disease. However, it does not appear to be associated with emergency cardiovascular-related hospital admissions or development of cardiovascular conditions.

For the elderly, living in cold homes can increase the risk of a loss of strength and dexterity, and of arthritis.

Living in a cold home is also associated with a higher risk of having poor mental health, which may be linked to fuel poverty and anxiety over paying heating bills.

In contrast, there is very little evidence on the health impacts of excess indoor heat. Although some literature suggests higher risk of mortality and certain heat-related conditions, there is no data on the significance of this association.

An important aspect of poor indoor heating that is not related to temperature is that of indoor air quality. Faulty, old or poor heating systems can leak carbon monoxide (CO) and lead to CO poisoning.

Literature on the wider societal impacts of poor indoor heating is scarce. This literature has established that poor heating and outdated heating technologies can have an effect on wider society by increasing air pollution and healthcare costs and by reducing school and workforce attendance and productivity.

The impact of new heating technologies and energy efficiency improvements on the indoor environment and on health

The evidence the research team reviewed shows that improved heating technologies and measures to increase energy efficiency of buildings are effective in improving several important aspects of the indoor environment. They do increase indoor temperature and perceived thermal comfort significantly. This is particularly important because increased indoor temperature may help to mitigate against the health conditions associated with living in a cold home. Furthermore, they result in reduced humidity levels indoors which may have positive implications for health.

At the same time, the evidence on whether improved technologies also result in lower levels of mould, which would be an important positive side effect of reducing humidity, is mixed. The most important factor for conflicting findings in this context seems to be whether appropriate ventilation was present.

Most studies reviewed also suggest that energy efficiency improvements, such as mechanical ventilation, decrease the level of indoor contaminants, such as that of nitrogen dioxide (NO_2). One study found that, depending on the combination of measures introduced and how well these are functioning, energy efficiency improvements may increase indoor radon levels.

Many studies reviewed explored the impact of energy efficiency improvements on mortality and on general health and wellbeing. These studies found that energy efficiency improvements are associated with a reduced number of excess winter deaths. They also found an association between a higher number of heat-related deaths in summer and an increase in indoor temperature.

Looking at more specific aspects of health, the impacts of energy efficiency improvements on health generally showed improved outcomes. In terms of respiratory health, including general respiratory health, asthma and other respiratory conditions, most studies identified a positive or neutral impact, but two studies actually found negative impacts on asthma and lung cancer.

In terms of circulatory conditions after the introduction of energy efficiency improvements, the findings suggest that the risk of this type of health issue may reduce. Although three out of four papers did report positive cardiovascular outcomes, none of these provided information on the statistical significance of this relationship.

Findings with regards to a potential impact of energy efficiency improvements on mental health suggested improvements or found no association. None of the studies reviewed found evidence suggesting that mental health had worsened.

Finally, the studies found no statistically significant evidence for the impact of energy efficiency improvements on other health outcomes, such as skin health, falls, ear infections and headaches. Some studies did find an association between energy efficiency improvements and better health outcomes for infections and headaches. But in some the association was not statistically significant, and in others the authors provided no information on statistical significance.

Conclusions and need for further research

This study has found relatively clear evidence concerning the negative health impacts of poor indoor environments. It has also found that improving heating technologies and introducing measures to increase energy efficiency of buildings are effective in improving several important aspects of the indoor environment.

It may therefore appear somewhat surprising that the evidence on the health effects of improved heating technologies and energy efficiency improvements is rather mixed. But it is important to highlight that the studies the research team reviewed covered a multitude of different factors of the indoor environment (temperature, humidity, existence of mould, air quality, level of radon, etc.), of different technologies and measures (insulation, ventilation, heat recovery, different heating technologies, etc.) and of different health conditions. This makes it challenging to draw any general, overall conclusions about the health effects of these improvements. Nonetheless, based on these findings, a number of important points can be made:

- One of the important underlying reasons for poor heating is fuel poverty. Members of households living in fuel poverty also tend to be more vulnerable to poor health. Therefore low-income families (who are most at risk of fuel poverty) need specific support to improve the condition of their homes.
- The evidence on the positive health impacts of energy efficiency improvements and better heating technologies is more mixed than expected. One important factor to ensure better health outcomes seems to be the proper functioning of the various technologies installed.
- The evidence identified in this review has focused on poor heating, implying mainly a problem with excess cold. But excess heat can be a problem, too, and it may become even more relevant in view of climate change. This study has shown that some energy efficiency improvements may contribute to problems of excess indoor heat in summer because greater insulation prevents heat from escaping. These risks should also be carefully assessed.

In relation to and further to these points, this rapid evidence review has identified multiple gaps in the evidence, such as:

- The impact of excess indoor heat as climate change contributes to increasing temperatures in the UK;
- The societal impacts of poor indoor heating, particularly the healthcare costs;

- The impacts of individual heating systems and energy efficiency measures on the indoor environment, including the unintended negative consequences and the effects when systems are not functioning correctly;
- The impacts of individual heating systems and energy efficiency measures on various aspects of health;
- The impact of poor heating, as well as of energy efficient heating, in the workplace; and
- The mechanisms that underlie the relationship between the impacts identified and the heating systems.

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Abbreviations and acronyms

AACODS	authority, accuracy, coverage, objectivity, date, significance
BEIS	Department for Business, Energy & Industrial Strategy
CI	confidence interval
CO	carbon monoxide
COPD	chronic obstructive pulmonary disease
EU-SILC	European Union Statistics on Income and Living Conditions
EWD	excess winter deaths
GBD	global burden of disease
IRR	incidence rate ratio
MD	mean difference
NICE	National Institute for Health and Care Excellence
NO_2	nitrogen dioxide
OR	odds ratio
aOR	adjusted odds ratio
PHE	Public Health England
PM	particulate matter
ROR	relative odds ratio
SAP	standards assessment procedure
SIDS	sudden infant death syndrome
WHO	World Health Organization

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Introduction

The importance of adequate indoor temperature and indoor air quality for health and well-being

According to recent European Union Statistics on Income and Living Conditions (EU-SILC), 6% of the population of the UK, or almost 4 million residents, are unable to keep their home adequately warm (EU-SILC, 2017). This may be for a number of different reasons, including housing deficiencies,[2] old and/or inefficient heating systems, and economic status. A combination of these is often referred to as fuel poverty, which is defined as the condition in which low-income households live in a home that cannot be kept warm at reasonable costs (BEIS, 2019).

While the above situation constitutes a serious problem in itself, it also has an impact on public health because excess cold can lead to greater mortality at a national level. Excess cold was a factor in 34,000 excess winter deaths on average in the past five years in England and Wales (Office for National Statistics, 2018).[3] Public Health England (PHE) considers the prevalence of cold, damp and poorly energy efficient homes in the UK as one of the main reasons for high numbers of excess winter deaths in the UK. Excess heat may be a problem too, in cases where heating systems do not adjust or cannot be adjusted well to changing outside temperatures or changing requirements during day and night. This health burden then leads to additional financial pressures on the healthcare system. One study estimates that health conditions associated with living in a cold home cost the National Health Service around £850,000 million per year (Nicol, Roys, & Garrett, 2011).

Some groups are much more likely than others to live in homes with poor heating. This may be a particular problem in the UK because of the older age of homes, which leads to problems in producing and retaining heat. For example, statistics suggests that as of 2016, 56% of homes were built before 1965 and that 35% of privately rented and 21% of privately owned homes were built before 1919 (Ministry of Housing, Communities & Local Government, 2016). In addition, the UK faces a complex energy market that can be difficult to navigate. For example, the Office of Gas and Electricity Markets has identified that some energy consumers are getting ‘left behind’ if they do not actively engage in finding a lower energy tariff and that consumers paying the highest energy prices are often those least able to afford them (Ofgem, 2017).

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[2] According to EU-SILC, 16% of the UK population was affected by such housing deficiencies as leaking roofs; damp walls, floors or foundations; or rot in window frames or floors.

[3] Excess winter deaths is defined as the observed total number of deaths in winter minus the average number of deaths during the rest of the year. It describes the number of additional deaths in winter months compared with summer months. More information can be found at https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/deaths/bulletins/excesswintermortalityinenglandandwales/2017to2018provisionaland2016to2017final

Living in a home that is too cold increases the incidence of heart attack, stroke, respiratory disease, influenza, falls and injuries, hypothermia, and mental illness (Gilbertson, Grimsley, & Green, 2012; Katiyo, Dorey, Bone, & Wookey, 2015; Marmot Review Team, 2011). Children and the elderly, who spend proportionally more time at home, are at a particularly higher risk. Furthermore, dampness and mould, which are a result of low indoor temperatures and poor ventilation, are related to the development of various health conditions, such as asthma (Reginald, Jaakkola, Hugg, Heikkinen, & Jaakkola, 2012), allergic rhinitis (Jaakkola, Quanash, Hugg, Heikkinen, & Jaakkola, 2013) and atopic dermatitis (Ha-Jung, Lee, Lee, Kang, & Hong, 2015). These health effects likely extend to working in a building with poor heating, because of the large amount of time people spend at work. However, there is limited research in this area. It is interesting to note that although the recommended indoor temperature within workplaces is 16°C to 24°C, this is not a legal requirement in the UK (UNISON, 2014). The increased prevalence of heat-related health conditions can lead to long-term socioeconomic impacts, through reduced productivity. This means both through absenteeism and presenteeism (i.e. a situation where a sick person comes to work but, in the long term, is less productive).

Excess cold is not the only hazard related to poor indoor heating. Indoor air pollution, which may be caused by gas stoves, gas boilers or other fuel-based heating technologies, is another one. Pollutants, such as benzene, carbon monoxide (CO), nitrogen dioxide (NO_2) and radon, can cause diseases ranging from headaches to cancer (World Health Organization, 2010). Inadequate ventilation may exacerbate the problem.

Recent improvements in the energy efficiency of buildings and heating improvements and their benefits

Recent decades have seen enormous improvements in terms of energy efficiency of buildings and heating technologies, both globally and in the UK more specifically.

More concretely (BEIS, 2017a; Chenari, Dias Carrilho, & Gameiro da Silva, 2016; Energy Saving Trust, 2019b, 2019a; Ionescu, Baracu, Vlad, Necula, & Badea, 2015), these improvements concern:

- The improved energy efficiency of buildings, achieved mainly through:
  - Better insulation of walls, roofs, and window and door frames;
  - Controlled ventilation (often in combination with efficient heating systems);
  - Heat recovery; and
  - Double- or triple-glazed windows.
- New heating technologies (mostly relying on renewable energy sources), including:
  - Ground source heat pumps;
  - Solar water heating;
  - Other innovative heating technologies; and

  - Thermal stores.
- Improvements in combustion-based heating technologies, mainly improved boiler technologies.
- Greater energy-saving efforts by consumers through:
  - Increased general awareness of the cost- and environment-related implications of unnecessary heating and
  - Smart meters that help to track and monitor energy use.

These improvements are often discussed and presented in light of their benefits for the environment, for the reduction of domestic heating costs and for energy security. The UK government has also, in its 'Clean Growth Strategy', explicitly and prominently mentioned the contribution that improved homes need to make to achieve the reduction in greenhouse gas emissions outlined in the Paris Agreement. The same strategy paper also makes frequent reference to the problem of fuel poverty and sets out concrete measures to reduce the problem through energy efficiency improvements (BEIS, 2017a).

There may be benefits in addition to the benefits outlined above. New and energy efficient heating systems may also benefit the ability of homeowners and tenants to keep their house adequately warm and would actually chose to do so. As a consequence, they would benefit from reduced risks to their health.

Independent of the temperature aspect, there are other potential benefits of shifting to energy resources that do not rely on combustion, for example of gas, oil or coal. These benefits relate to indoor air quality, which also has a clear impact on health. At the same time, it is conceivable that there are certain negative impacts of 'green buildings' on indoor air quality, relating, for example, to ventilation. Because ventilation of highly energy efficient buildings is often automated, the amount of fresh air coming into the house (or the amount of 'poor' air leaving the house) is sufficient.

The objectives of this study and its research questions

The UK Department for Business, Energy & Industrial Strategy (BEIS) commissioned RAND Europe to assess and synthesise the available evidence on the impact of homes with poor heating and of homes with energy efficient heating systems. More specifically, the study team and BEIS jointly developed the following four overarching research questions:

1. What is the impact of poor indoor heating on health?
2. What are the wider societal impacts of poor indoor heating?
3. What is the impact of energy efficiency improvements, renewable heating technologies and smart technology on the indoor environment?
4. What is the impact of energy efficiency improvements, renewable heating technologies and smart technology on health?

The team addressed these questions through a rapid evidence assessment, which balances the benefits of a structured literature review approach with the need to conform to resource and time constraints.

Methodology

To identify evidence of the impact of poor indoor heating on health and wider society, and of the impact of introducing energy efficient heating improvements on health and the indoor environment, the research team conducted a rapid evidence assessment. This type of review involves a systematic yet flexible approach to searching the literature that allows for a large amount of literature to be identified and analysed in a short space of time (Center for Evidence-based Management, 2019). Further information on the methodological approach can be found in the accompanying technical report.[4]

The study team and BEIS jointly developed four overarching research questions (outlined in the introduction) and related sub-research questions. The sub-research questions helped to guide the rapid evidence assessment and to support the development of a precise search strategy. If articles covered the overarching questions but not the sub-research questions, the research team still included them for full-text extraction. Further detail on the sub-research questions can be found in the accompanying technical report.

After development of the research questions, the research team created inclusion and exclusion criteria. These criteria are used to determine which articles should be included for full-text analysis during the screening and data-extraction phase. The research team developed the exclusion and inclusion criteria in consultation with BEIS. It then refined them during the development of the search protocol and the early screening phase based on the research questions and the types of articles identified. One of these criteria was to only include studies conducted in high-income countries. The criteria used and reasoning behind their use can be found in the accompanying technical report.

The rapid evidence assessment involved searching three databases. The research team identified academic literature using PubMed. It identified grey literature by searching two different sources: the National Institute for Health and Care Excellence (NICE) Evidence Library and the European Union Energy Poverty Observatory. The team developed the search terms for PubMed in consultation with BEIS. For the NICE Evidence Library search, the research team used keywords from the PubMed search to identify relevant literature. The team only extracted search hits for screening if the first page of the search included at least one paper relevant to one of the research questions *and* if the hits on the first page had not already been identified. The EU Energy Poverty Observatory is a fairly new initiative. Therefore the research team only searched the term ‘health’, for publications since 2010. Finally, during the inception phase of the project, BEIS provided an additional list of 72 resources they had identified as possibly being of relevance to the project. This resulted in 12,289 articles for

[4] Hocking, L; Gkousis, E; Smith, P & Gehrt, D. (2019) Heat, energy efficiency, smart technology and health: A review of evidence from high-income countries, with a focus on the UK. Technical report. BEIS Research Paper 2020/022. London: Department for Business, Energy and Industrial Strategy.

screening. The search strings used, and further information on the literature search protocol, are presented in the technical report.

The screening phase resulted in 645 articles that the team considered to be relevant to the research questions and that had been conducted in high-income countries. This number of papers is very high for a rapid evidence assessment, and the research team would be unable to extract the data from all of these. Therefore, the research team, in consultation with BEIS, defined an approach that would reduce the number of articles down to a more manageable number and ensure the articles analysed were relevant to a UK context, whilst also basing the results and conclusions on high-quality evidence. It was decided that, out of the 645 relevant papers, the following articles would be taken forward:

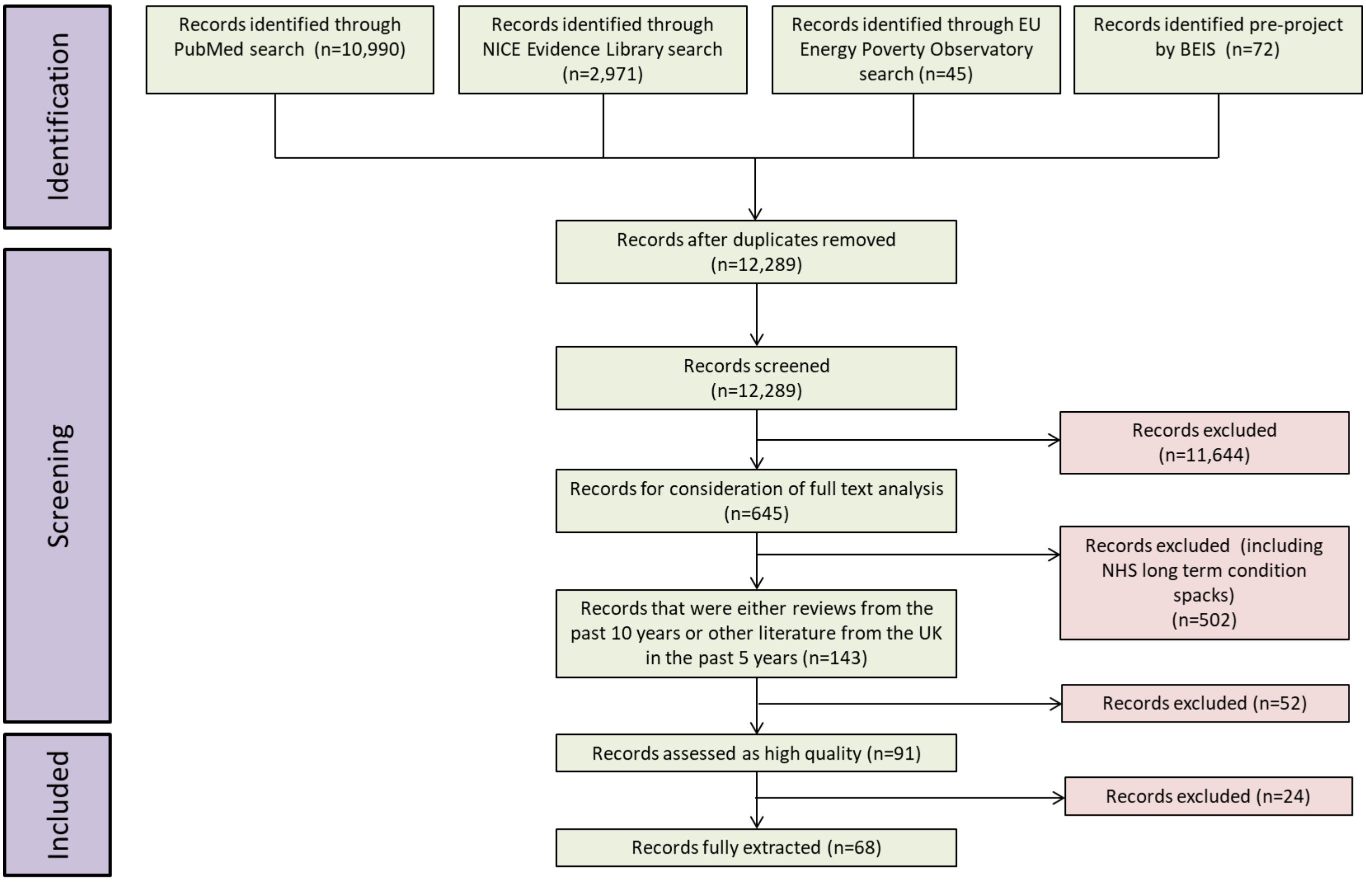
- All reviews from any high-income country since 2010 were included to provide a summary of the literature over a longer-term period and from a wider geographical scope.
- Academic and grey literature from the past five years conducted in the UK was included to ensure the evidence collected is relevant to a UK context and is up to date, and to help to reduce the number of papers to a more manageable number.[5]

This resulted in 143 papers being taken forward to the next stage, which involved quality assessment of the articles. This phase ensures the conclusions arrived at are based on high-quality research. The team developed the academic criteria based on criteria previously used by RAND Europe (Guthrie et al., 2017). It adapted the grey literature criteria from the Authority, Accuracy, Coverage, Objectivity, Date, Significance (AACODS) checklist, which is recommended for assessing the quality of grey literature (Tyndall, 2010). The specific criteria used are presented in the accompanying technical report. The distribution of articles covering each research question showed that there was very little high-quality evidence for research question 2 (i.e. the impact of poor heating on wider society). The research team were interested in exploring the wider societal impacts of poor heating. Therefore, in consultation with BEIS, the study team included articles from the past 5 years from countries other than the UK that related to research question 2.

The research team created an Excel extraction template to identify relevant information from the literature. Details on the types of information extracted are presented in the accompanying technical report. Analysing the full text provides more detail than is provided in the abstract. The research team excluded additional papers at this stage because reading the full text revealed the papers to be out of the scope of the research or duplicates. This left a total of **68** articles that were fully extracted. A summary of these numbers and how they were reached is presented in Figure 1.

[5] It should also be noted here that the 645 papers deemed to be relevant to the study after screening included 208 NHS long-term conditions packs. After consultation with BEIS, these were excluded at this point in the study. Because the data provided was at a local level and highly repetitive across all 208 documents, the Long-Term Condition Packs were deemed not to be of use.

Figure 1: Preferred reporting items for systematic reviews (PRISMA) flow diagram



Source: Adapted from Moher, Liberati, Tetzlaff, & Altman (2009).

Limitations and caveats

Although the research team used a systematic approach and covered both academic and grey literature for the literature search to identify as much of the relevant evidence as possible, there are limitations to the approach.

First, the team did not conduct a systematic review of the literature and so did not search all potentially relevant databases. This means it is possible that some relevant articles were not identified. The team attempted to mitigate this as best as possible by searching a number of different literature sources and reiterating the search terms to ensure they were broad enough to capture as much relevant literature as possible.

Second, because of the large number of articles found to be relevant after screening (645), the research team had to introduce a fairly restrictive approach to reduce the total to a more manageable number. Restricting studies published pre-2014 to reviews only means some relevant articles published pre-2014 may have been excluded. As the number of articles to review has been relatively high throughout the research, a single reviewer screened and extracted each source independently. However, the researchers discussed any uncertainties on an ad hoc basis, particularly at the start of the screening and extraction phases, to ensure all three researchers were following a consistent approach to screening and extraction.

Unfortunately, because of the large number of articles identified for full-text review (68), the research team were unable to look up each study included in the literature reviews of these 68 studies. Therefore the analysis of identified literature reviews relies on the review authors' interpretation of the results of the studies they reviewed. Our discussion below references the review only, rather than the original study. The research team caution that the review may not always be an accurate representation of the results of the original study. The study team has provided references to important grey literature guidelines and datasets relating to poor heating, e.g. the WHO guidelines on indoor temperature, to direct the reader to important documentation in the field.

Many of the reviewed studies did not provide information on why the impacts they identified occurred as a result of the type of heating system in the home. The research team have provided details on the causal link where possible, including the reviewed studies authors' speculations or hypotheses. However, the research team were often unable to discuss the reason why certain impacts arose.

Finally, the research team have reported p-values[6] and other statistical significance information, including confidence interval (CI),[7] odd ratio (OR),[8] incidence rate ratio (IRR)[9] and relative odds ratio (ROR),[10] in footnotes. Not all of the reviewed studies included this information, and it is unclear why. The research team were therefore unable to comment on the significance of all relationships reported.

[6] P-values show whether a result occurred by chance, or whether the relationship found is statistically significant (i.e. not down to chance). Relationships considered to be statistically significant have p-values <0.05.

[7] Confidence intervals provide a range of values within which it is likely that the true value lies. If a confidence interval is 'cross 1', the 95% confidence interval lies between 0.9 and 1.1, and this suggests there are no differences between the two arms of a study.

[8] Odds ratios statistically quantify the association between two interventions.

[9] A rate ratio is used to compare the incidence rates of events at certain points in time.

[10] The odds ratio is the ratio of the odds of an event in the treatment to the odds of the event in a control group. The odds of an event is the number of events divided by the number of non-events.

The health and wider societal impacts of poor indoor heating

This chapter will outline the results covering research questions 1 and 2, the health and wider societal impacts of poor indoor heating. It will also cover the scale of the problem of poor indoor heating in the UK and the groups most at risk of living in poorly heated homes. The section below provides a summary of the important points from this chapter.

Summary of the impacts of poor indoor heating

The findings from the rapid evidence assessment highlight the wide variety of health and societal impacts of poor heating that has been measured in recent research. The details of the various impacts of each heating-related issue can be difficult to identify across the literature sources. At the end of this section, Table 1 and Table 2 provide an overview of the direction of impact for each heating-related issue and whether these results were significant. This summary is broken down by the sub-research questions relating to this chapter.

What are the impacts of homes and workplaces with poor heating (and of its consequences, such as mould and damp) on adults' and children's physical and mental health, including perceptions of health?
As Table 1 shows, a wide variety of negative health impacts are linked to homes with poor heating. Interestingly, all of this evidence relates to the effects of living in homes with poor heating. None of the literature reviewed focused on the effects from exposure to poor heating in the workplace. Unless otherwise specified, these results are relevant to adults.

Mortality was found to increase when indoor temperatures were either too high (although the significance of this relationship is not made clear in the literature) or too low (because of a lack of central heating and insulation). Mortality from a wide range of different health conditions was found to increase with domestic coal use, possibly because of the pollution associated with this.

The studies the researchers reviewed tested various health impacts of lack of central heating, old boilers and poor heating systems in general. The evidence for the direction of impact was not always clear. Evidence was found with regard to a worsening of mental health outcomes and an increased risk of CO poisoning. Significance information was not provided for these outcomes. No association was identified for general respiratory health, general physical health strength and dexterity, or hospital admissions. Mixed evidence was found for cardiovascular health, asthma and respiratory infections. Some studies found significant links between these health outcomes and poor heating, whereas others found no association. The causal link between poor heating systems and adverse health outcomes was often not discussed in the reviewed literature. Some authors hypothesised that low temperatures lead to damp and mould development, which may contribute to poor respiratory and cardiovascular outcomes.

The use of solid fuel and biomass for heating were found to significantly increase the risk of mortality and respiratory conditions, specifically asthma (in children), chronic obstructive pulmonary disease (COPD) and lung cancer. A specific risk of COPD is seen for women when they are in homes using biomass for fuel. It is likely that this is a result of the carcinogenic pollutants found in smoke produced from burning biomass.

Some studies explored the health effects of excessively high temperatures. The study authors linked excess indoor temperature to multiple poor health outcomes and mortality, as discussed above. Cold homes are significantly linked to poor respiratory health and high blood pressure, and also (but not significantly) to asthma, poor mental health and poor strength and dexterity. Two studies found that asthma in children worsened with cold temperatures, which may indicate that children are more at risk compared with adults. No significant association was found between low indoor temperatures and poor general physical health or circulatory health outcomes. When exploring the effects of high indoor temperatures, links were found to heat-related conditions, such as heat cramps, heat rash, heat oedema, heat syncope, heat exhaustion and heatstroke. Information on the significance of this relationship was not provided.

Poor insulation was found to worsen many of the assessed health outcomes. Poor insulation is significantly linked to asthma and not significantly linked to poor general physical health. No association was found between insulation and emergency hospital admissions. In studies looking at specific types of insulation, lack of or poor cavity wall insulation and floor insulation was linked to a higher risk of mortality. The relationship is significant for the former but not for the latter. As previously discussed, these worse health outcomes may be a result of low indoor temperatures contributing to the development of damp and mould.

Mixed health outcomes were seen with regard to poor ventilation. Relationships were found between poor ventilation and CO poisoning, respiratory infections and, in children, allergic conditions. However, significance information was not provided for these. For asthma and emergency hospital admissions, some studies found significant links to poor ventilation, whereas others found no association. In children, poor ventilation was found not to be linked to asthma or wheeze.

Using gas cooking was found, for children, to increase the risk of asthma to a statistically significant level. But it had no association with wheeze. However, NO_2 pollution, linked to the use of gas, was found to increase the risk of wheeze in children. No information on significance is provided. Despite the significant link between gas cooking and asthma, using gas for heating was not found to be associated with asthma in children. Both gas heating and generators were found to increase the risk of CO poisoning. No information on significance is provided.

Which populations are most affected by conditions related to poor indoor heating?
The research team identified certain vulnerable groups that are more at risk of developing the health conditions associated with poor indoor heating. The factors that increase the risk of developing the health conditions associated with cold homes include existing physical and mental health conditions, disabilities, mobility difficulties, being very young or old, pregnancy, recently having had a fall, and addiction.

Those with existing physical or mental health conditions are also more at risk of suffering the health conditions associated with homes that are too hot.

What are the morbidity and mortality rates associated with having homes that are too hot or too cold, draughty, damp or with poor gas stoves or boilers?
Much of the reviewed literature did not provide information on the *rates* of mortality and morbidity, with a few exceptions. NICE estimates that a total of 24,000 excess winter deaths (EWD) occur in England and Wales per year (NICE, 2015). The number of EWDs directly attributable to living in a cold home varies, with estimates at varies in the literature, including 0.24% (Stafford, 2015), 10% (Bridgeman et al., 2016) and 21.5% (Public Health England, 2019; Marmot Review Team, 2011). NICE estimates suggest that those living in the coldest 10% of homes face an increased mortality rate of 2.8% with every degree Celsius drop in outdoor temperature (NICE, 2016).

Is there an optimal temperature for sleeping?
Although the reviewed literature did not provide specific values for the optimal temperature for sleeping, multiple sources recommend that indoor temperature remain between 18°C and 24°C. Bedroom temperature was suggested to fall at the lower end of this range, close to 18°C, indicating that sleeping temperature should be slightly below day-time temperature.

What proportion of a person's air pollution exposure (and consequential health issues) is a result of heating systems and gas cookers or hobs?
This information was not covered by the reviewed literature.

How do heating consumption and associated behaviours vary depending on people's health conditions?
Much of the reviewed literature did not provide information on how health conditions influence heating consumption. However, a report by National Energy Action (2018) reported evidence that those at home for longer periods during weekdays have a lower heating consumption, of a median of 9.4 hours per day. Those more likely to be at home during the day are more likely on a low income or unemployed (also associated with fuel poverty) and the very old and the very young.

What are the indoor air pollution-related health impacts of oil boilers, gas boilers, heat pumps, biomass boilers and coal back boilers?
As discussed previously, the use of gas is linked to indoor NO_2 pollution, which, evidence suggests, is linked to wheeze. The significance of this link is not provided.

Using coal as a domestic fuel source has been linked to higher mortality from a range of conditions, as also discussed earlier. This includes significantly higher mortality from various respiratory conditions, cardiovascular conditions and cancers. It is likely that this relationship is a result of greater pollution associated with coal use. Coal was also associated with a higher risk of CO poisoning. Significance for this association was not provided.

The use of biomass was significantly associated with a higher risk of asthma, lung cancer and COPD. Again, this is most likely because of the increased pollution released.

The research team did not find any information for the air pollution-related health impacts of oil boilers or heat pumps.

What are the economic costs of health conditions related to poor indoor heating?
The evidence suggests that there are higher economic costs associated with poor heating. There are costs both for individual homes, because of higher energy bills and lower earnings in later life, and for the health service, because of the additional financial costs to care for individuals with the health conditions associated with poor heating. None of these studies provided information on the significance of these relationships.

At an individual level, one reviewed study identified that foetal exposure to high temperatures (over 32°C) is linked to lower annual earnings in late adulthood.

Poor boilers (back boilers, non-condensing regular boilers and non-condensing combi boilers) were found to contribute to higher energy bills and thus to a higher risk of fuel poverty.

The health conditions linked to living in a poorly heated home are associated with higher financial costs faced by the health and social care system. These additional costs run into the millions of pounds for the NHS. Interestingly, associated mental health conditions are estimated to cost the NHS more than associated physical conditions.

What are the impacts of homes that are too hot, too cold, or damp on children's academic attainment?
Evidence suggests that poor insulation and ventilation at home leads to children taking more days off school. Improved heating leads to fewer days off school, and so does improved ventilation. The relationship is significant for the former but not significant for the latter. While it can be speculate that poor heating and poor ventilation therefore also impact on children's educational attainment, the research team has not identified any direct evidence for this.

How does the temperature of workplaces affect productivity?
Improvements in home insulation were found to reduce the number of days adults took off work. Poor ventilation in the workplace was found to significantly increase sleepiness at work. A Greek study found that an increase in ventilation at work improved cognitive performance, which was estimated to equate to a US$6,500 increase in productivity per year. This suggests that low temperatures and poor ventilation contribute to additional days off work and poorer productivity.

Table 1: Summary of results for individual types of poor heating on health outcomes

	Mortality	Poor general physical health	Emergency hospital admissions	Poor general respiratory health	Asthma	Allergic conditions	Wheeze	Respiratory infections	Lung cancer	COPD	Heat-related conditions	High blood pressure	Poor general circulatory health	CO poisoning	Other cardiovascular	Mental health	Strength and dexterity
Lack of central heating	↑*	↑ ↔		↔									↑* ↔			↑	↔
Old boilers														↑			
Poor heating (general)		↑*	↔	↑	↑			↑*						↑		↑	
Use of solid fuel	↑*							↑↔	↑*					↑			
Use of biomass					↑*				↑*↔	↑*							
High indoor temperature	↑*										↑						
Low indoor temperature	↑*	↑*↔	↔	↑*	↑			↑				↑*	↑*		↔	↑	↑
Poor insulation (general)		↑	↑*↔	↑													
Poor cavity wall insulation	↑*																
Poor floor insulation	↑*																
Poor ventilation		↑	↑* ↔		↑ ↔	↑	↔	↑						↑			
Gas cooker					↑*		↔										
Gas heating					↔									↑			

Generators														↑			
NO_2 pollution							↑*										
Asbestos									↑								

** Indicates that at least one study investigating this relationship found a statistically significant link.*

↑ Indicates that the risk increases, ↔ indicates that there is no association and ↓ indicates that the risk decreases. Where two or more arrows are provided, this indicates mixed evidence in the literature.

Table 2: Summary of results for individual types of poor heating on wider societal outcomes

	Lower school attendance	Lower work attendance	Lower work performance	Higher outdoor pollution	Higher health care costs	Lower earnings in adulthood	Higher energy bills
Poor heating (general)	↑			↑	↑		↑
Use of solid fuel				↑			
High indoor temperature						↑	
Low indoor temperature					↑		
Poor insulation (general)	↑	↑					
Poor ventilation	↔		↑				
Gas heating					↑		

↑ Indicates that the risk increases, ↔ indicates that there is no association and ↓ indicates that the risk decreases.

The prevalence of poor indoor heating is relatively high in the UK, and some populations are at a greater risk than others

As part of research question 1, to help us understand what indoor temperature could be considered as excessive, the research team explored the recommendations for optimal indoor temperature, the extent of poor indoor heating in the UK and the populations more at risk of living in homes with poor heating.

The optimal indoor temperature for healthy individuals is 18°C to 24°C
Multiple articles provided information on the optimal indoor temperature for healthy individuals, drawing on guidance provided by the World Health Organization (WHO), Public Health England and NICE.

Two papers the research team reviewed referred to WHO guidance[11] that recommends that indoor temperature should be between 18°C to 24°C for healthy individuals, as this poses the smallest risk to health. These papers highlight that the bedroom should be cooler than the living room (18°C and 21°C, respectively) (Ambrose et al., 2018; Anderson, Carmichael, Murray, Dengel, & Swainson, 2013). However, NICE guidance notes that these WHO recommendations are fairly old and do not provide information as to the optimal temperature for those who are not healthy (NICE, 2015). In addition, Thai et al. (2019) found that humans adapt to higher indoor temperatures, and so the WHO recommendation of 18°C to 24°C should not be universally applied.

The team also reviewed indoor temperature guidance from the UK, published by PHE and NICE. These guidelines are more recent than the WHO recommendations. PHE recommends similar indoor temperatures to WHO. PHE recommends that homes should be heated to at least 18°C in winter to minimise health risks to sedentary individuals wearing suitable clothing. PHE also suggests that a temperature slightly above this may be beneficial for the elderly with existing health conditions (Katiyo, Dorey, Bone, & Wookey, 2015; Public Health England, 2019). PHE also recommends a minimum temperature of 18°C overnight in the homes of the elderly with existing medical conditions. It states that keeping the temperature at 18°C overnight may be less important for younger people with sufficient clothes and bedding (Katiyo, Dorey, Bone, & Wookey, 2015; Public Health England, 2019). NICE guidance provides similar recommendations, namely, that the general comfortable temperature indoors for most of the EU population is 21°C (NICE, 2015). Finally, according to the 'Cold Weather Plan for England', a temperature between 16°C and 20°C in infants' rooms is recommended to reduce the risk of Sudden Infant Death Syndrome (SIDS) (Katiyo, Dorey, Bone, & Wookey, 2015).

[11] The research team did not identify these WHO guidelines through the literature search, as they were published before 2014, which was the year the research team went back to for non-review articles. These guidelines can be found at https://www.worldcat.org/title/health-impact-of-low-indoor-temperatures-report-on-a-who-meeting-copenhagen-11-14-november-1985/oclc/19276717

These guidelines primarily focus on recommending minimum indoor temperatures to prevent cold-related health outcomes. However, it is also important to not let indoor temperatures become too high. PHE's 'Heatwave Plan for England' suggests that indoor temperature should not exceed 26°C for vulnerable populations, including those in care homes. In addition, temperatures should not exceed this in rooms where susceptible groups spend more of their time (Public Health England, Department of Health and Social Care, & NHS England, 2014).

These recommendations suggest that the ideal indoor temperature is 18°C to 21°C and that it may need to be slightly higher to minimise the risk of health impacts for vulnerable populations, such as the elderly and those with existing health conditions. However, these recommendations and guidelines often do not provide information on the evidence base behind these suggestions (except for NICE). It is therefore sometimes unclear how these conclusions were reached. Interestingly, in the articles reviewed relating to poor heating, the authors did not make clear whether the temperatures they were referring to were considered to be low for the general population or for those more at risk of developing health conditions related to living in a cold home, who may require higher indoor temperatures compared with the healthy population.

The prevalence of poor indoor heating is fairly high in the UK and is strongly linked to fuel poverty

Many of the articles reviewed provided statistics on the prevalence of fuel poverty, energy inefficiencies and specific types of poor heating systems in the UK. One study found that 10% of low-income UK households cannot afford to keep their home adequately warmed (Braubach & Fairburn, 2010). Certain groups are at risk of fuel poverty, with evidence suggesting 1.6 million children and 4.5 million elderly people are living in fuel poverty in the UK (Bridgeman et al., 2016). These groups, and others, are discussed in more detail in the following section.

NICE explored the prevalence of energy inefficient homes across England. Standards Assessment Procedure (SAP) ratings show how well a building retains heat. A score of 69 or above out of 100 is considered to be energy efficient. SAP ratings across England vary. In 2012 only 18% of homes were deemed to be energy efficient, and 9% scored less than 30 (equating to 2 million homes), indicating low energy and environmental performance (NICE, 2015, 2016).

Two of the articles reviewed explored the prevalence of specific types of poor indoor heating, cooking and ventilation systems. In one study, the prevalence of air conditioning was reported to be 3% across UK homes (Khare et al., 2015). National Energy Action[12] explored the prevalence of different boiler types considered to be poor, as well as space heaters and gas cookers. It found that 13% of homes have combi-non-condensing boilers, 20% have regular non-condensing boilers,[13] 10% have no boiler and 3% have a back boiler[14] (National Energy

[12] National Energy Action is a charity that aims to reduce fuel poverty in England, Wales and Northern Ireland.
[13] Non-condensing boilers remove waste gases using a flue, which is inefficient and has a negative impact on the environment. Condensing boilers recycle the gases using a heat exchanger, which is more energy efficient

Action, 2018). It also found that 47% of homes in the study had at least one space heater, such as a gas fire or wood burning stove, which is a potential source of indoor pollution. Many of the participants used space heating appliances to ‘top up’ heating during winter, but some also used it as the primary source of heating to save money (National Energy Action, 2018). Finally, National Energy Action found that 59% of their study participants had a gas cooker (hob and/or oven), a source of CO pollution. This is similar to the average across England of 55% (National Energy Action, 2018).

Some groups are more at risk of living in homes with poor heating

Across the literature, a range of groups were identified that are more at risk of living in homes with poor heating compared with the general population, including:

- Low-income households;
- Households with members with existing health conditions;
- Households with very young or old members; and
- Households with certain types of housing factors, including living in older homes, living in rural locations, and owning or privately renting homes (compared with those in social housing).

In addition to these four factors listed above, one paper discussed the importance of behaviours and education in influencing the risk of living in a cold home (Mould & Baker, 2017). These authors found that a lack of heating education can lead to a higher risk of being in fuel poverty, for example, not being aware that heating on the maximum setting for a short period increases costs compared with heating on a lower setting for a longer period of time.

Low-income households

Low-income households[15] were consistently identified as being one of the main groups more likely to live in homes with poor heating than those on higher incomes, primarily because of the greater risk of being in fuel poverty.

Many studies linked the greater risk of living in homes with poor heating to fuel poverty, meaning people either cannot afford to use the heating or choose not to use it to save money (Ambrose et al., 2018; Fisher & Dorning, 2016; National Energy Action, 2018; NICE, 2015). For example, a national survey in Ireland found that 30% of homes in fuel poverty have indoor temperatures below 18°C, compared with 11% of homes not in fuel poverty (Ambrose et al., 2018). Similarly, National Energy Action identified that homes relying on secondary sources of

and results in a lower environmental impact. More information can be found at https://sse.co.uk/help/energy/energy-efficiency-and-saving/condensing-boilers

[14] Back boilers are installed behind fireplaces or gas fires and use the heat generated from these to produce hot water. These are not efficient boilers (working below the UK government’s recommendations for boiler efficiency), cost more to run and bring with them a risk of explosion. More information can be found at https://www.boilerguide.co.uk/articles/back-boiler

[15] The reviewed studies did not provide a definition of low income, so the research team cannot be sure what income threshold the studies based their samples on.

heating, such as gas or open fires, or who use secondary sources as replacement for their primary heating source, are more likely to be low-income households, as it is perceived to be cheaper to continue to use these sources rather than fixing the primary source or buying a new one (National Energy Action, 2018). These authors also found a statistically significant link between cold homes and people receiving means-tested benefits.[16] Interestingly, this study also reported results of a UK Government survey that found people who spend more time at home on weekdays (which may indicate low income) have their heating on for an average of 9.4 fewer hours per day than those who spend more time out of the house (National Energy Action, 2018).

In addition to the risk of fuel poverty, there are other factors leading low-income households to have a higher risk of living in homes with poor heating. Braubach and Fairburn (2010) identified that groups of lower socioeconomic status are more at risk of living in inadequate housing conditions and having increased exposure to environmental risks at home. Single-parent households are also more likely to be in fuel poverty, leaving children of single parents at particular risk of living in homes with poor heating (Bridgeman et al., 2016; Mould & Baker, 2017). In addition, people facing sudden life changes, such as divorce, can be at greater risk of fuel poverty at a time when they are not eligible for state support because of the short-term, rapid onset of their circumstances (Mould & Baker, 2017). Finally, immigrants are also at greater risk as they are more likely to live in poor housing conditions and need to deal with new and complex energy markets after initially moving to the UK (NICE, 2015).

Ethnic minority households are also considered to be more at risk of fuel poverty than white households (Bridgeman et al., 2016; Garrett, Piddington, & Nicol, 2014; NICE, 2015). Garrett et al. (2014) explored differences in fuel poverty by ethnicity and found that 15% of ethnic minority homes were in fuel poverty in 2011 compared with 10% of white households.[17] However, the same authors note that, although ethnic minorities are more at risk of fuel poverty, other statistics indicate they are at less of a risk of living in a cold home. Estimates from 2010 suggested that 4% of ethnic minority households live in homes with an excess cold compared with 6% of white households (Garrett et al., 2014).

Although the majority of the literature reviewed that provided information on the groups more at risk of living in homes with poor heating included low-income households, National Energy Action identified some low-income factors that were not associated with living in cold homes (National Energy Action, 2018). Although these authors found a statistically significant link between receiving means-tested benefits and cold homes, they found no significant association between living in a cold home and homes with poor boilers (non-condensing

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[16] p=0.006.

[17] However, it is interesting to note that the prevalence of fuel poverty among different ethnicities varied depending on the definition of fuel poverty used. Garrett et al. (2014) estimates are based on Hills' definition of fuel poverty. This measure takes into account housing costs and the difference between a household's required fuel costs and what these would need to be for the household to not be in fuel poverty. Garrett et al. (2014) use a different definition. They assume that 10% of income is spent on heating to get homes to a sufficient temperature. By this measure, the prevalence of fuel poverty is actually the same across ethnic minority and white households, at 15% for both in 2011.

boilers), income below £16,000 before tax, subjective fuel poverty or actual fuel poverty status. Interestingly, there was also a significant association between living in non-deprived areas and cold homes.[18] However, the authors note that this result may be skewed because of the finding that 97% of the rural homes in the study sample were from non-deprived areas (National Energy Action, 2018). Those with incomes below £16,000 per year may be at lower risk of living in homes with poor heating as they are eligible for government support.

Pre-existing medical conditions

As with low-income, homes with members with existing medical conditions, including physical disability, are more at risk of living in homes with poor heating. This increased risk may be linked to those with existing health conditions or disabilities requiring an indoor temperature above that needed by healthy individuals (NICE, 2015) but also because of a higher risk of this group being in fuel poverty.

Some sources provided information on the causal link between poor health and living in a cold home and, as with low-income, this appeared to be fuel poverty (i.e. those with ill health are more likely to live in a cold home because they are at greater risk of fuel poverty). For example, one article reported estimates from the 2012 Hills Review of Fuel Poverty in England[19] that 34% of homes in fuel poverty have a member with a disability or long-term medical condition (Bridgeman et al., 2016). People with existing medical conditions and those living in households with income 60% below the median are at particular risk of living in cold homes (Bridgeman et al., 2016).

However, as it did for low income, the National Energy Action study disputed some of the evidence above. This study found no statistically significant association between poor boilers (non-condensing boilers) and ill health or disability (National Energy Action, 2018). However, this study only explored the link between one type of poor boiler. It is likely that wider socioeconomic factors have greater influence than the presence of one type of boiler.

Age of the individual

An individual's age is considered to influence their likelihood of living in a home with poor heating. Two sources identified children as being more at risk of living in cold homes, particularly those in early childhood (Maidment, Jones, Webb, Hathway, & Gilbertson, 2014; NICE, 2015). Neither article specified the reason for this increased risk.

The majority of the literature focused on the risk faced by those aged 65 and over (Bridgeman et al., 2016; Fisher & Dorning, 2016; Ige et al., 2018; Liddell & Guiney, 2015; Maidment et al., 2014; Mould & Baker, 2017; NICE, 2015; Shiue, 2016). This greater risk of living in a home

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[18] $p=0.001$.

[19] The Hills review was not identified through the literature search, as it was published before 2014, which was the year the research team went back to for non-review articles. This report can be found at Hills, J. (2012). Getting the measure of fuel poverty: Final report of the Fuel Poverty Review. London: Department of Energy and Climate Change. As of 21 October 2019: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/48297/4662-getting-measure-fuel-pov-final-hills-rpt.pdf

with poor heating was thought to be due to a range of reasons, including that they spend more time indoors at home (Ige et al., 2018). As mentioned before, spending more time at home has been linked to using heating for an average of 9.4 fewer hours per day (National Energy Action, 2018). One study speculates that the elderly are at greater risk of fuel poverty because they may not be aware of the energy support schemes they are eligible for (Mould & Baker, 2017). Another speculates that they may have smaller budgets to live off, leading to older people using their heating less to save costs (Fisher & Dorning, 2016).

A study by Shiue (2016) found that the risk of living in a home with poor heating may peak at early old age and reduce over time. This author found that those aged 80 and over were significantly less likely to live in a cold home compared with those aged 50 to 79.[20] This may be because of the additional social support received in older age.

While the evidence discussed in this section supported a link between age and the higher likelihood of living in a home with poor heating, evidence gathered by National Energy Action did not support such a link. Their study found no significant association between those aged 65 and over or children aged 0 to 15 living in homes with poor boilers (non-condensing boilers) (National Energy Action, 2018). However, this again only focuses on the effects of one type of poor boiler. The risk of living in cold homes is likely to be a result of multiple factors.

Housing factors

Housing factors that can lead to a higher likelihood of living in a home with poor heating include homes that are energy inefficient, living in a rural location, older age of homes and privately renting or owning a home.

Energy inefficient homes are thought to lead to a greater risk of low indoor temperatures (BEIS, 2017b; Bridgeman et al., 2016). BEIS identified that homes in fuel poverty are less likely to have energy efficient systems. Over 40% of fuel poverty homes are rated Band E or below (classed as energy inefficient), compared with 50% of homes not in fuel poverty (BEIS, 2017b). The extent of energy efficiency links to the age of homes, with older homes more likely to have lower energy efficiency ratings (NICE, 2015).

Homes in rural locations are also considered to be more likely to have poor heating (Bridgeman et al., 2016; Jones & Mays, 2016; National Energy Action, 2018; NICE, 2015). For example, National Energy Action found a statistically significant association between living in rural areas and having a cold home (National Energy Action, 2018).[21] This higher risk may be a result of the difficulty in connecting to the main gas network, causing complexities in installing heating systems and meaning households must rely on more expensive forms of heating (Jones & Mays, 2016; NICE, 2015) and so are at greater risk of fuel poverty.

Homeownership status is thought to influence the risk of living in a home with poor heating (Bridgeman et al., 2016; Jones & Mays, 2016; National Energy Action, 2018; NICE, 2015).

[20] $p=<0.001$.
[21] $p=<0.0001$.

Privately owned and privately rented homes were found to have a higher risk of poor heating compared with social housing (Bridgeman et al., 2016; Jones & Mays, 2016; National Energy Action, 2018; NICE, 2015). For example, one literature review identified that 19% of privately rented homes in England have poor heating, compared with the national average of 11% (Bridgeman et al., 2016). Relatedly, Jones and Mays (2016) found that participants living in local authority or housing association homes reported feeling warm, had central heating and insulation, and had repairs to heating systems undertaken quickly. In contrast, participants who owned their home reported having inadequate heating systems. National Energy Action found that homes using secondary heating sources considered poor, such as gas or open fires, were more likely to be rented homes, which may be because the occupants lack authority to address housing quality (National Energy Action, 2018). Privately owned and rented homes are also more likely to have lower energy efficiency ratings than social housing. Lower ratings are linked to a greater risk of having poor heating, as mentioned previously (NICE, 2015). However, National Energy Action identified that homes in the private rented sector are no more likely to have poor boilers than are other types of homes (National Energy Action, 2018).

Poor indoor heating appears to have a negative impact on some health outcomes, although the evidence is mixed

The majority of papers reviewed examined the impacts of poor indoor heating on health. Many of these concluded that it has a negative impact on health, with only a small number finding non-significant associations between certain aspects of the indoor climate and health. Many of these papers explored the impact on mortality and general health. Some also covered respiratory conditions, heat-related conditions, circulatory conditions, mental health conditions, and strength and dexterity.

Excess indoor temperature and coal use are associated with a greater risk of mortality and poor physical health, with certain groups being more at risk of these effects

Multiple papers focused on investigating the association between excess indoor heat and cold, and the use of coal for fuel, on mortality and general physical health outcomes.

Domestic use of coal contributes to the development of a range of health conditions, including cancer

Phillips et al. (2018) found statistically significant increases in mortality from respiratory conditions, cardiovascular conditions and some forms of cancer later in life as a result of the higher levels of air pollution linked to domestic coal use in the 1950s. According to this study, other cancers showed no significant change as a result of air pollution exposure from domestic coal use, including urinary, reproductive (except cervical cancer) and haematological cancers. Interestingly, melanoma and brain cancer were associated with a slightly reduced relative risk of mortality after domestic coal use. The authors speculate that a lower risk of mortality from melanoma was a result of less sun exposure in the areas of the UK with higher coal use (which is generally used more in the north of the country). The lower risk of mortality from brain cancer was thought to be due to residual confounding as a result of the high levels of mortality for this cancer and high sensitivity of the analysis.

Excess indoor heat can contribute to worsening of physical health, including mortality

Two literature reviews explored the mortality risk of excess indoor heat. Anderson et al. (2013) reviewed studies conducted in the UK and found that a lack of relief from heat at night is a significant contributing factor to heat-related mortality. These authors hypothesised that this is because higher temperatures in the morning contribute to heat exposure and subsequent mortality. Another paper in this review also found an association between warm bedroom climate and episodes of poor sleep. However, the reason for this link is not made clear (Anderson et al., 2013). The literature reviewed suggests that excess indoor heat is more dangerous for vulnerable subgroups. Those with cardiovascular or respiratory disease, diabetes, chronic mental disorders, or other pre-existing medical conditions are thought to be at greater mortality risk from heat exposure; the reason for this additional risk is not made clear (Huang et al., 2011). None of the papers reviewed here provided information as to the significance of these associations.

Living in a cold home contributes to excess winter deaths and contributes to poor health, particularly in certain vulnerable populations

Much of the literature reviewed in this study focused on exploring the mortality impacts of cold homes, including fuel poverty (which can be an indicator of low indoor temperatures). For many studies that looked at the impact of low indoor temperatures, the primary outcome measure was excess winter deaths (EWD). NICE estimated that there are 24,000 EWD in England and Wales annually (NICE, 2015) and that 83% of the cold-related EWD are in people aged 75+ (NICE, 2016).

Other sources estimate the number of EWD associated specifically with living in a cold home, with estimates varying across different sources. Stafford (2015) modelled the effects on mortality and calculated that there are 58 deaths per year in the UK that can be linked to living in a cold home. Bridgeman and colleagues (2016) use the Hills review estimate that 10% of EWD could be related to living in cold homes (Bridgeman et al., 2016). This figure is lower than the one reported in a report by the Marmot Review Team. Their report estimates that 21.5% of excess winter deaths are attributable to living in the coldest one quarter of homes (Marmot Review Team, 2011).

Multiple studies concluded that indoor temperatures are associated with EWD. A large pan-European analysis of 14 countries found fuel poverty to be associated with excess winter mortality, although the reason for this link is not made clear (Tanner, Moffatt, Milne, Mills, & White, 2013).[22] Another study, also conducted across 14 EU countries, demonstrated that living in cold homes leads to greater risk of mortality. Countries with the poorest thermal efficiency show the highest level of excess winter mortality (Portugal: 33% mortality increase; Spain: 21%, Ireland: 21%, UK: 19%) (Braubach & Fairburn, 2010). The authors do not discuss the causal link. A review of EWD found that the seasonal mortality in homes with the lowest indoor temperatures was 1.20 times[23] that of the warmest homes, a significant difference.

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[22] p=0.005.
[23] Range from 1.09 to 1.32.

Evidence discussed in this review suggests that the increased risk of mortality may be a result of cold indoor temperatures leading to higher risk of developing cardiovascular and respiratory conditions (London School of Hygiene & Tropical Medicine, Public Health England, & University College London, 2014).[24] Finally, according to NICE, those living in the coldest one quarter of homes are three times more at risk of being part of excess winter deaths than those in the warmest one quarter of homes. Those in the coldest 10% of homes face an increased death rate of 2.8% with every degree Celsius drop in outdoor temperature, compared with rate of 0.9% in the warmest 10% of homes (NICE, 2016). These EWD associated with excess indoor cold are most likely the product of worsening respiratory and cardiovascular problems (Bridgeman et al., 2016; London School of Hygiene & Tropical Medicine et al., 2014).

Tanner et al. (2013) used a literature review to explore the general health outcomes of living in homes that are too cold and of fuel poverty. They do not specify the health outcomes of focus. These authors found evidence from three studies that composite fuel poverty measures are significantly associated with adverse winter health outcomes. The causal link between these associations was not made clear. However, seven UK studies these authors reviewed found non-significant associations between indicators of deprivation and adverse winter health outcomes, such as mortality, hospitalisations and hypothermia (Tanner et al., 2013).

Multiple papers reviewed, primarily from PHE and NICE, identified groups that are more at risk of poor health as a result of living in cold homes. These groups are fairly similar to those more at risk of living in homes with poor heating outlined in the previous section. Older people are one of the groups more at risk of suffering adverse health effects as a result of living in cold homes. They are more at risk of heart attack, stroke, circulatory conditions, respiratory conditions, flu, and falls and injuries (NICE, 2016). A study examining the effects of cold outdoor temperatures found that older people are particularly susceptible because they are more likely to have complex health needs (Fisher & Dorning, 2016).

Other groups more at risk of developing health problems associated with cold homes, as identified by PHE (Katiyo, Dorey, Bone, & Wookey, 2015; Public Health England, 2019) are:

- Those with existing medical conditions, particularly cardiovascular and respiratory conditions – such as chronic obstructive pulmonary disease, heart disease and childhood asthma – and diabetes;
- Those with mental health conditions that impact self-care, including dementia;
- Those with disabilities;
- Those with mobility difficulties or who are housebound;
- Young children (under the age of 5);
- Pregnant women (posing a risk to the foetus);
- Those who have attended hospital because of a fall;

[24] p=0.002.

- Those who move in and out of homelessness; and
- Those with addictions.

However, PHE does not provide information on why these groups are at a greater risk of suffering the health impacts associated with living in a cold home.

A lack of central heating, poor ventilation and poor insulation can contribute to a worsening of physical health

A small number of studies looked at specific heating systems, including a lack of central heating, and poor ventilation and insulation, to explore the impact on mortality or general health outcomes. A positive link between central heating and indoor temperature was established by one review, which found an association between the absence of central heating and lower indoor temperature (London School of Hygiene & Tropical Medicine et al., 2014). One study found a significant association between lack of central heating and the risk of dying in winter in UK adults over the age of 65 (Ige et al., 2018).[25] According to Tanner et al. (2013), the absence of, or reduced satisfaction with, central heating was associated with adverse winter-related health outcomes. None of these studies identifying links between lack of central heating and health outcomes provided information on why there is a link. However, a study of an intervention study where free central heating was installed in homes of Scottish people over 65 concluded that their evidence did not demonstrate a clear influence on health (Liddell & Guiney, 2015).

A systematic review of quantitative observational studies identified three studies that found poor thermal insulation to be associated with adverse winter-related health outcomes (Tanner et al. 2013). The authors of a pan-European study found significant negative associations between winter mortality and cavity wall insulation and a weaker association with floor insulation (London School of Hygiene & Tropical Medicine et al., 2014).[26] The reason why these associations may occur was not discussed in these studies.

Finally, a UK study looking at ventilation found that elderly participants without electrical upgrades (which included kitchen ventilation) were statistically significantly more likely to have an emergency hospital admission.[27] This also extended to other age groups, and when looking specifically at respiratory admissions.[28] The authors suggest this may be a result of poor ventilation increasing the risk of falls (because of slip hazards) and contributing to poor respiratory health (because of increases in damp and mould and low temperatures). The authors observed no impact when they looked at all age groups together for emergency admissions for cardiovascular conditions (Rodgers et al., 2018).[29] Sundell et al. (2011) conducted a systematic review looking at associations between ventilation and health across 23 studies from Sweden, the USA and other high-income countries and found that short-term

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[25] OR 1.016, 95% CI 1.009 to 1.022.
[26] $\beta=-2.56$, $p=0.02$ for cavity wall insulation; $\beta=1.01$, $p=0.03$ for floor insulation.
[27] IRR 0.61, 95% CI 0.53 to 0.72, p=<0.01.
[28] IRR 0.66, 95% CI 0.58 to 0.76, p=< 0.01 for emergency admissions of all age groups; IRR 0.60, 95% CI 0.48 to 0.74, p=< 0.01 for respiratory emergency admissions of all age groups.
[29] IRR 0.79, 95% CI 0.65 to 0.96, p=0.016.

sick leave increased with lower ventilation rates, possibly because of increased levels of airborne rhinovirus, which leads to colds. No information on the significance of this relationship is provided.

The evidence for impact on respiratory health is mixed, although the general trend indicates a worsening of respiratory health with poor indoor heating
Respiratory outcomes were a commonly measured impact among the reviewed literature. This included impacts on general respiratory health, asthma, allergic conditions, wheeze, lung cancer and respiratory infections. The studies focused on a range of different types of poor heating systems.

General respiratory health

Multiple papers explored the impact on general respiratory health as a result of living in homes with poor indoor heating. The majority of these found a negative impact on respiratory health. One found no association.

Three studies looking at living in homes with poor heating found a worsening of general physical health as a result of living in these conditions. In an intervention study focused on homes with poor ventilation, heating and insulation, residents of unimproved houses in the UK reported a significant increase in non-asthma-related chest problems, including bronchitis, and in dry throat, itchy eyes, blocked nose and runny nose compared with residents of homes that had been improved (which included improvements to ventilation and heating systems) (Ige et al., 2018).[30] In addition, an English longitudinal study found that living in a cold home was associated with significantly worse lung condition (Shiue, 2016).[31] A modelling study by Stafford (2015) identified that 138 cases of respiratory conditions each year in the UK are associated with living in a cold home. These studies do not discuss the causal link between these heating-related issues and general respiratory health.

Other papers identified an association between poor respiratory health and poor indoor heating specifically in vulnerable groups. Evidence from a literature review focusing on the elderly suggests that respiratory symptoms were 1.97 times (range 1.03 to 3.76) more prevalent if the house was cold in winter and 2.39 times (range 1.07 to 5.36) if the resident was dissatisfied with the insulation in their home (London School of Hygiene & Tropical Medicine et al., 2014). The same review outlined evidence from a World Health Organization study that suggests that respiratory symptoms were 2.1 times more prevalent in children if the resident was dissatisfied with the heating systems in their home (London School of Hygiene & Tropical Medicine et al., 2014).[32] Finally, NICE outlines that those with existing respiratory conditions are more at risk of developing further respiratory illness and other health problems from living in a cold home (NICE, 2015). These studies do not make clear the link between poor respiratory health and poor indoor heating.

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[30] Mann-Whitney test, $z=2.8$, $p=0.05$.
[31] $p=<0.001$ for vital forced capacity; $p=0.0001$ for forced expiratory flow; $p=0.004$ for peak expiratory flow.
[32] 95% CI 1.0 to 4.38.

Despite the evidence above suggesting that poor indoor heating is linked to poor respiratory health, a study of homes in Glasgow found no statistically significant link between the presence of central heating and the prevention of respiratory conditions. There was also no significant link between central heating and recovery from respiratory illnesses (Curl & Kearns, 2015).

Asthma

Many of the papers reviewed explored the association between poor indoor heating and asthma. Although some of these found mixed results depending on the source of poor heating, many found an increased risk of developing asthma.

Certain types of fuel, including gas and biomass, are linked to the development of asthma. Lin, Brunekreef, & Gehring (2013) conducted a meta-analysis of 42 studies published between 1977 and 2013. They estimated a significant impact of exposure to gas cooking in childhood on the odds for lifetime asthma.[33] Similarly, Sharpe, Thornton, Nikolaou, & Osborne (2015b) identified a significant increase in risk of seeing a doctor for asthma in the previous 12 months when gas was used as a primary source of heating.[34] The authors of these two studies speculate that this link may be a result of pollutants released from gas systems (although perhaps not NO_2) triggering the development of asthma. Two papers explored the impacts on asthma of using biomass for fuel. Dick et al. (2014) estimated that the use of biomass fuel for cooking is associated with increased risk of asthma in children. However, the reason for this link is not made clear.[35]

Two papers looked at the effects of ventilation on asthma and found poor ventilation was associated with worse asthma outcomes. A systematic review looking at associations between ventilation and health found that asthma symptoms increase with lower ventilation rates. No p-value is provided, and the causal link is unclear from the paper (Sundell et al., 2011). In addition, a national survey conducted in the USA found that the use of a dehumidifier was an independent predictor of lower levels of some asthma triggers and mould (Krieger et al., 2010).

Two studies found evidence that asthma outcomes are worsened by living in a cold home. Neither study provided details on statistical significance. A survey by Ambrose et al. (2018) showed that the cold of their home affected both asthmatic and non-asthmatic children's health and well-being. Similarly, participants in study reported that cold temperatures impacted on the health and well-being of both children with asthma and of others in the home (Tod et al., 2016). Neither study provided information on the causal link between asthma and low indoor temperatures.

Two studies found no significant link between poor heating and asthma outcomes. Although biomass heating was found to link to poor asthma outcomes by Dick et al. (2014), the same authors did not find a significant link when looking at gas heating. In addition, although Sharpe and colleagues found some negative asthma effects from using biomass for heating, they did

[33] OR 1.32, 95% CI 1.18 to 1.48, p=0.000.
[34] OR 1.6, 95% CI 1.1 to 1.23, p=0.001 to 0.01.
[35] OR 4.3, 95% CI 3.0 to 5.0.

not find a significant association with visiting a doctor for asthma in the past 12 months in homes with poor ventilation or poor heating (Sharpe et al., 2015b).[36]

Allergic conditions

Only one paper looked at the link between allergic conditions and poor indoor heating. This was a Swedish study examining the association between ventilation rates and allergic symptoms in children. It found that children with asthma, rhinitis and atopic eczema lived in homes with lower ventilation rates than the control group. No p-value is provided in the review that referenced this study (Sundell et al., 2011). The reason for this association was not discussed.

Wheeze

Three papers explored the link between poor indoor heating and wheeze. One of these found that poor indoor heating is associated with increased risk of wheeze, whereas the two others did not.

In a study examining the impact of ventilation on wheeze in children, there was no association between measured ventilation rate of the whole house and the risk of having a wheeze (Sundell et al., 2011). Lin et al. (2013) conducted a meta-analysis of 42 studies published between 1977 and 2013 and estimated a non-significant impact of gas cooking on the odds for wheeze in children. Lin et al. (2013) also examined the effect of NO_2 (which is released by gas cookers) on child health and found that it is associated with a significantly increased risk of wheeze.[37]

Respiratory infections

Two papers investigated whether poor indoor heating was associated with a risk of developing respiratory infections, with mixed outcomes.

A systematic review found limited evidence for an association between pollution released from burning solid fuel (which can be used for heating) and risk of acute lower respiratory infection in adults. In that review, two studies found a significant adjusted increased risk of acute lower respiratory infection, two identified a univariate association, and four found no significant association (Jary et al., 2016).

Another systematic review, this time looking at associations between ventilation and health across Sweden, the USA and other high-income countries, suggest that respiratory infections increase with lower ventilation rates. However, the authors provided no information on the significance of this link or the cause of the association (Sundell et al., 2011).

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[36] OR 0.8, 95% CI 0.5 to 1.5 for poor ventilation and OR 1.0, 95% CI 0.6 to 1.8 for poor heating.
[37] OR 1.12, 95% CI 1.04 to 1.21, p=0.002.

Lung cancer

Three studies investigated the risk of developing lung cancer after exposure to pollutants in the home (following the burning of coal and biomass for fuel and cooking) and asbestos (which can be used in insulation).

Two systematic reviews explored the link between burning coal and biomass for fuel at home and developing lung cancer. Both demonstrate an increased risk of cancer, although with some variation among different groups. A systematic review and evaluation of the evidence for the Global Burden of Disease (GBD) 2010 study, which involved collecting data on the different durations of exposure to biomass fuel, suggested that there is a statistically significant trend in increasing lung cancer risk for men.[38] However, there was no significant association for women (Bruce et al., 2015). The authors used further evidence from pooled studies from Europe, the USA, Canada and Asia and calculated a significant odds ratio of 1.19 for men and 1.19 for women[39] for lung cancer (Bruce et al., 2015). The authors suggest this may be a result of high levels of carcinogenic pollutants in biomass smoke. Another systematic review and meta-analysis of studies estimated that the risk of lung cancer among users of solid fuels (which include wood and coal) is 70% higher than among non-users. This finding is statistically significant.[40] The magnitude of association between coal use and lung cancer was greatest,[41] followed by biomass (predominantly wood[42]) and mixed fuel[43] (Kurmi, Arya, Lam, Sorahan, & Ayres, 2012). However, it should be noted that this systematic review used data from many different countries, including developing countries, and that the results specific to high-income countries could not be differentiated.

A further heating-related factor that could lead to an increased risk of lung cancer is the presence of asbestos, sometimes used in insulation, which is responsible for roughly 275 new cases of asbestos-related lung cancer each year in Great Britain. A report by the Health and Safety Executive states that asbestos is the second most common cause of lung cancer. Research suggests there are around 2,500 asbestos-related lung cancer deaths per year. It is unclear from this report how many of these are related to domestic asbestos exposure (Health and Safety Executive, 2018).

Chronic Obstructive Pulmonary Disease

Finally, a meta-analysis explored the impact of poor indoor heating on the risk of developing COPD. This study found that women from low-income backgrounds who used biomass for fuel were 1.38 times more likely to be diagnosed with COPD than low-income women who had not been in a home where biomass is burnt for fuel.[44] This effect was still apparent when the smoking status of individuals was taken taking into account. This review does not provide

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[38] OR 1.06 (<25% use of wood for fuel in lifetime); OR 1.13 (25 to 50% lifetime); OR 1.37 (>50% lifetime), p=<0.01.
[39] 95% CI 1.02 to 1.39 for men and 95% CI 0.94 to 1.51 for women.
[40] OR 1.70, 95% CI 50% to 94%, p=<0.001.
[41] OR 1.82, 95% CI 1.60 to 2.06.
[42] OR 1.50, 95% CI 1.17 to 1.94.
[43] OR 1.13, 95% CI 0.52 to 2.46.
[44] OR 1.38, 95% CI 1.28 to 1.57.

details on why this increased risk occurs after exposure to biomass smoke (Sana, Somda, Meda, & Bouland, 2018).

Heat-related conditions are thought to increase with higher indoor temperatures, but the evidence is unclear

One report reviewed focused on the health impacts of exposure to high indoor temperatures. The ‘Heatwave Plan for England’ (Public Health England et al., 2014) outlines the types of conditions that can occur as a result of exposure to excess indoor heat and the groups most at risk. It states that excess heat can increase the risk of developing respiratory and cardiovascular conditions – including heat cramps, heat rash, heat oedema, heat syncope, heat exhaustion, and heatstroke – and of suicide. High outdoor temperatures are directly linked to excess indoor heat, but some houses are more at risk of overheating. Risk factors include being on the top floor, particularly a top-floor flat facing south or south-west, and being in lightweight buildings, in which the insulation is often on the outside of the building, which can lead to overheating.

The ‘Heatwave Plan for England’ outlines the groups that are more at risk of developing these conditions from living in a home that is too hot: older people (over 75), females, people living alone or isolated, those in urban areas, people with drug or alcohol dependency, homeless people, infants (under 4), those with existing medical conditions and those whose health, housing or economic circumstances put them at risk of harm from high temperatures. Additionally, children who are overweight, taking medication, have disabilities or have complex needs may be at increased risk of adverse side effects. However, this report did not provide any evidence for these claims or any information on the significance of the association between indoor heat and the conditions outlined above.

Living in a cold home appears to contribute to an increase in blood pressure and may slow the recovery from cardiovascular illness

The studies the research team reviewed discuss the impact of living in cold homes on circulatory conditions. The evidence suggests an increased risk of higher blood pressure and slower recovery from circulatory conditions. Poor heating systems can also lead to leakage of CO, leading to CO poisoning. However, it is important to note that living in a cold home may not directly lead to the development of cardiovascular conditions. There are other contributing factors.

According to an English longitudinal study, living in a cold home was associated with higher blood pressure and cholesterol levels (Shiue, 2016).[45] The effect on blood pressure is reinforced by a further study examining the impact of indoor temperature on blood pressure. It found that systolic and diastolic blood pressure significantly increased as temperature was reduced.[46] A one-degree reduction in indoor temperature was associated with a 0.5 mmHg increase in blood pressure (Zhao, Jivraj, & Moody, 2019). In addition, a large Scottish survey

[45] Blood pressure $\beta -0.64$, 95% CI −0.75 to −0.52, p=<0.001 and high cholesterol $\beta -0.02$, 95% CI −0.04 to −0.01, p=0.011.

[46] p=<0.001.

suggested that people living in homes with temperatures below 18°C are twice as likely to have high blood pressure (Ambrose et al., 2018). Further evidence showed that people were significantly more likely to recover from circulatory conditions after central heating was introduced, compared with those without central heating (Curl & Kearns, 2015).[47] None of these studies provide information about to why these associations may occur.

None of the reviewed studies provided data on the prevalence of carbon monoxide poisoning. However, data from the Office for National Statistics suggests prevalence is fairly low. In 2017, accidental CO deaths in England and Wales totalled 59, with 11 of these occurring at home. It cannot be said for certain that these are linked to heating sources, but it is likely that some of these are (Office for National Statistics, 2017). Three studies explored the association between the quality of heating systems and CO poisoning.[48] CO poisoning risk increases during winter because of increased cold weather and loss of electrical power. This leads to greater use of gas-powered generators and other alternative heating systems, as well as reduced housing ventilation. Generators and gas supply systems were the third leading cause of CO deaths in the UK (Lisbona & Hamnett, 2018). This view is also shared in the 'Cold Weather Plan for England', which states that cold weather outdoors can lead to greater risk of CO poisoning indoors because of increased use of poorly maintained or ventilated boilers, cooking appliances and heating systems; this is also reflected in NICE guidance (NICE, 2016; Katiyo, Dorey, Bone, & Wookey, 2015). As expected, older boilers are more likely to be involved in a CO incident. Two out of three CO fatalities in 2014 to 2015 in the UK involved boilers over 30 years old, and the risk increases with appliances more than 12 years old (National Energy Action, 2018). Using combustion heaters, for example, gas and solid fuel heaters, for long periods increases the risk of CO exposure, particularly if there is a lack of ventilation. Those spending more time at home are more at risk from CO exposure and to the effects of CO poisoning, such as those who are older, in ill health or unemployed (National Energy Action, 2018).

Certain circulatory conditions are not associated with living in cold homes. In an English longitudinal study of cold homes, there were no significant differences in pulse rate and blood fibrinogen and ferritin level[49] in those who lived in cold homes (Shiue, 2016).[50] In an English intervention study among the elderly, there was no change in the risk of emergency admission in the intervention group (who received various housing improvements, including insulation, heating system improvements and extractor fans) compared with the control group.[51] This

[47] OR 2.63, 95% CI 1.17 to 5.92, p=<0.05.
[48] CO poisoning affects the ability of the blood to carry oxygen around the body because it binds to the haemoglobin in the red blood cells, preventing these cells from carrying oxygen.
[49] Fibrinogen is a blood protein that helps to form clots to slow bleeding after an injury. Ferritin is a blood protein that stores and releases iron around the body.
[50] This study also explored the changes in other blood biomarkers. The authors found that living in a cold home was significantly associated with lower vitamin D levels (0.98, 95% CI 0.72 to 1.23, p=0.001), lower white blood cell counts (0.08, 95% CI 0.06 to 0.11, p=0.005), higher insulin-like growth factor levels (−0.10, 95% CI −0.15 to −0.04, p=0.007) and higher haemoglobin levels (−0.05, 95% CI −0.07 to −0.04, p=0.001). However, no association was found between living in a cold home and changes in C-reactive protein level or blood glucose level (Shiue, 2016).
[51] IRR 0.91, 95% CI 0.82 to 1.01, p=0.072.

includes emergency admissions specific to cardiovascular conditions,[52] and the finding was the same when looking at all age groups (Rodgers et al., 2018). Additionally, another study found no statistically significant link between central heating and the incidence of development of circulatory conditions (Curl & Kearns, 2015).

Mental health can be affected by living in fuel poverty and a cold home, partly because of anxiety over the financial costs of heating

Evidence suggests that living in a cold home can affect people's mental and psychological well-being. This may be linked to the fact that cold homes are often a direct result of low income, which may itself be a cause of poor mental well-being.

Stafford (2015) conducted a modelling study to explore the effects of living in a cold home on mental health. The author identified that 1,369 cases of common mental disorders in the UK were linked to living in a cold home in 2011 to 2012. In addition, a survey carried out in 2010 showed that, of those living in low-income houses, 47% said the cold had made them feel anxious or depressed, and 30% reported worsening of an existing health condition (NICE, 2016). Participants who had poor heating before an intervention reported improved well-being (life satisfaction) with replacement or installation of heating (49% reporting bad health, dropping to 27% after intervention) (Bennett, Dayson, Eadson, Gilbertson, & Tod, 2016). Finally, in an energy efficiency intervention study, 48% of residents reported suffering a mental health problem before receiving the intervention as a result of living in a cold home (Stockton, Ruse, Garrett, Garlick, & Powells, 2018).

This worsening of mental health is likely to be linked to financial worries and demonstrates how challenging home environments can negatively impact on mood and psychological health (Bennett et al., 2016).

The elderly are more at risk of a reduction in strength and dexterity when living in cold homes

Four studies provided evidence on the impact of indoor heating on people's strength and dexterity. Stafford (2015) conducted a modelling study on the effects of living in a cold home and found that this was linked to 117 cases of falling at home in the UK in 2011 to 2012. Ambrose et al. (2018) found that cold and damp homes can impact mobility, increase risk of falls, increase symptoms of arthritis and reduce strength and dexterity (increasing risk of non-intentional injury). Another study estimated that arthritis symptoms in seniors were 1.92 times (range 1.16 to 3.16) more prevalent if the house was cold in winter (London School of Hygiene & Tropical Medicine, Public Health England, & University College London, 2014).

However, another study found that after an intervention to add heating systems to the homes of elderly people, there was no statistically significant difference between control and intervention groups in emergency hospital admissions for injuries (Rodgers et al., 2018).

[52] IRR 0.85, 95% CI 0.71 to 1.03, p=0.093.

Poor heating can affect the wider society through a reduction in school and work attendance and productivity and through an increase in air pollution and financial costs

This section will outline the relevant results of the literature reviewed on the wider societal impacts of poor indoor heating and ventilation. It will discuss the impacts experienced on attendance at both school and work, performance (including factors affecting performance), air pollution, workforce productivity and economic outcomes, including adult earnings, increased energy costs and NHS costs.

As discussed in the methodology section, the restrictions put in place during the literature search (all reviews from the past ten years and other papers from the past five years from the UK) meant the research team had a very low number of relevant papers for this topic. Therefore the research team, in consultation with BEIS, decided to include all relevant papers from the past five years from any high-income country, not just the UK. However, the research team still found very few studies in this area that had been published in recent years.

School and work attendance appear to increase with improved heating and ventilation
A small number of studies suggest a positive impact from improved indoor heating and ventilation on school attendance. One indicated a positive impact on work attendance. A literature review identified two studies exploring the impact on school attendance and focused specifically on asthmatic children. One was conducted in New Zealand and the other in the UK (Ige et al., 2018). The New Zealand study evaluated the effects of installing heaters described as “non-polluting and more effective” (e.g. wood pellet burner, flued gas) in children’s homes. The study found that children in the intervention group took 1.80 fewer days off from school annually.[53] The UK study resulted in higher school attendance in the intervention group after the installation of ventilation systems in homes.[54] This finding was not statistically significant.

Another study, focused on low-income communities in New Zealand, identified an association between having insulation and a reduction in the number of days children took off school.[55] The authors also included information on work attendance and reported an association between improvements in insulation and a reduced odds of adults taking time off work[56] (Ige et al., 2018).

This information indicates that homes with poor ventilation and heating systems may have higher rates of school and work absenteeism. The reason for the link between heating-related issues and lower attendance is not made clear.

[53] 95% CI 0.11 to 3.13.
[54] p=0.091 for all-cause absence and p=0.053 for asthma-related absence.
[55] OR 0.49, 95% CI 0.31 to 0.80.
[56] OR 0.62, 95% CI 0.46 to 0.83.

Excess temperature and poor ventilation at work can reduce performance
Studies generally indicate that there is a positive association between decreased ventilation and poor performance. However, the reason for this link is not made clear.

In a study by Vehvilainen et al. (2016), a reduction in ventilation led to an increase in sleepiness and decrease in concentration. Both are factors affecting performance. Self-reported sleepiness increased in a non-ventilated room,[57] but did not significantly change in a ventilated room. Lower concentration was noted in the non-ventilated room, and neither momentary alertness nor perceived mental stress differed significantly between the non-ventilated and ventilated rooms. No p-values are provided for any of these latter measurements.

One study tested the effects of increased ventilation on performance and found a positive effect (MacNaughton et al. 2015). When ventilation was increased from 20 cfm/person to 40 cfm/person, participant scores in cognitive performance increased from the 62nd percentile to the 70th percentile on average across all domains evaluated. No p-value is provided. These authors also calculated a positive economic benefit from increased productivity as a result of improved ventilation in office buildings. Examining three different ventilation scenarios and four different heating, ventilation, and air conditioning system strategies, the authors calculated that this improved performance by 8%. This is the equivalent of a US$6,500 increase in employee productivity each year. These findings may indicate that workplaces without sufficient ventilation face lower productivity in employees.

Poor domestic heating contributes to rising outdoor air pollution levels
Two studies link residential heating to increased levels of air pollution.

Gualtieri et al. (2015) showed that residential heating in Italy significantly increased the number of limit exceedances of particulate matter (PM) 10,[58] by a correlation coefficient factor of 0.35.[59] The study aimed to assess the extent to which residential heating and other factors contribute to urban PM10 concentrations during air pollution critical episodes. The authors concluded that major emission drivers, including residential heating, played a marginal role.

Phillips et al. (2018) explored the long-term impacts of using coal for fuel on air pollution. The authors identified that the areas of the UK that used high levels of coal for domestic heating in the 1950s also had a high level of microparticulate matter measured in 2001. They provide no p-values for the significance of this difference.

Exposure to excessive temperatures in utero can lead to lower earnings later in life
Isen, Rossin-Slater and Walker (2017) found evidence of a link between early exposure to high temperatures and a negative impact on economic outcomes in adulthood. They evaluated the association between the length of time exposure to high temperatures in utero and in early

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[57] p=<0.05.
[58] PM10 refers to particulate matter 10 micrometres or less in diameter.
[59] Significant at 1% level.

childhood and economic outcomes approximately 30 years later for 12 million individuals born between 1969 and 1977 in the USA. The statistically significant results of the study suggest that an extra day of exposure to temperatures above 32°C in utero or in the first year of life is associated with around $30 (in 2008 US dollars) lower average annual earnings at ages 29 to 31. Isen et al. (2017) also mentioned that there was little evidence that more economically disadvantaged populations disproportionately experience high-temperature anomalies during gestation. However, the study assumes that changes in external temperature affect indoor temperature, a factor that limits any conclusions regarding the effects of poor indoor heating and ventilation. And it does not provide information as to what the causal link is between exposure to higher temperatures in utero and earnings in later life.

Cold homes can lead to increased financial burdens for individual households and the healthcare system

A number of studies explored the financial impacts of homes with poor heating. These identified impacts at an individual home level, through increased energy costs, and at the healthcare system level, through increased healthcare costs.

One paper explored the financial costs of homes with poorly functioning boilers, including back boilers, non-condensing regular boilers and non-condensing combi boilers (National Energy Action, 2018), at an individual home level. It found that homes with these types of boilers cost more to run than those with more efficient types (condensing boilers). This was found to contribute to homes being in fuel poverty, with 15% of homes with non-condensing boilers being in fuel poverty compared with 10% of those with condensing boilers. Faulty heating systems may worsen this effect. The authors speculate that these types of systems are turned off less because of concerns that they may not turn on again, which can lead to higher energy costs.

Sarigiannis, Karakitsios, & Kermenidou (2015) calculated the healthcare costs associated with greater morbidity and mortality as a result of exposure to pollution released from biomass burning for space heating in Greece. They estimated the morbidity costs of chronic bronchitis, cardiovascular disease, and respiratory problems in Greece from 2012 to 2013 to be around 30 million euros and the mortality costs to be from 200 to 250 million euros.

Stafford (2015) estimated the costs of cold homes to wider society through increased burden on the health and social care system using data from 2011 to 2012.[60] The results from this

[60] A variety of local data sources were used to estimate these costs. Deaths were taken from the West Midlands Public Health Observatory and cover the years 2008–2011 “modified by a national ‘Marmot Adjustment Coefficient’ of 0.215”. Cardiovascular deaths were derived from “HHSRS national harm-to-health likelihood coefficient for the hazard of excess cold (1/380) multiplied by the number of local households in which at least 1 person aged 65 or above resides”. Respiratory illnesses were derived similarly to cardiovascular illnesses, namely, “the HHSRS national harm-to-health likelihood coefficient for the hazard of damp and mould (1/464) multiplied by the number of local households in which at least 1 person aged 16 or below resides”. The number of falls was derived from “the number of local households in which at least 1 person aged 65 or above resides multiplied by the HHSRS national harm-to-health likelihood coefficient for the hazard of falls on the level (1/135), plus the same number of households multiplied by the HHSRS national harm-to-health likelihood coefficient for the of hazard of falls on stairs (1/245), with the sum modified by the

study are presented in Table 3. As this table shows, the health and social care costs associated with living in a cold home run into the millions, and the well-being and social costs of mental health conditions are significantly larger than those of physical conditions.

Table 3: Healthcare costs associated with cold homes in the UK (in £million)

	Deaths	Cardiovascular conditions	Respiratory conditions	Falls at home	Common mental health disorders	Total cost
Loss of well-being costs	£1.86	£1.60	£1.31	£1.12	£9.64	£15.53
NHS primary secondary and tertiary cost plus social care cost	-	£0.39	£0.60	£0.33	£2.11	£3.44
GDP loss	-	-	-	-	£0.93	-
Total social costs	£1.86	£1.99	£1.91	£1.46	£12.68	£19.90
Total social cost per case	£0.03	£0.02	£0.01	£0.01	£0.019	£0.08

Source: Stafford (2015).

Garrett et al. (2014) assessed the impact of ethnic minorities living in poor housing on NHS costs by analysing data from the English Housing Survey. The study includes some measures of poor heating, such as excessive indoor temperatures and indoor air pollution. Excess indoor cold in minority ethnic homes was found to cost the NHS just more than £159 million, damp and mould (which may increase as a result of poor heating) more than £58 million and CO

national 'Marmot Adjustment Coefficient' of 0.215 to account for falls in the home not attributable to low indoor temperatures". Common mental disorders were derived from "the total number of local households multiplied by the national proportion of adults using less domestic fuel than needed to heat the home due to cost worries who also suffer from a common mental disorder with the proportion adjusted to account for those using less fuel due to cost worries who suffer from a common mental disorder due to other causes, and with the product reduced to cover only those affected who receive treatment". Loss of wellbeing was derived from "£40,000 for the value of 1 year of healthy and disability-free life, combined with WHO Disability Adjusted Life Year weights of 1 for death, 0.4 for cardio-vascular disease, 0.25 for respiratory illness. 0.3 for falls in the home and 0.2 for common mental disorders, with morbidity weights taken from World Health Organization. These weights are adjusted for the probability that those afflicted would not otherwise enjoy full health". NHS social care costs for cardiovascular disease were "£3,124 per case for NHS Primary, Secondary and Tertiary Care and non-NHS Social Care; for respiratory illness. £4359 per case for NHS Primary, Secondary and Tertiary Care and non-NHS Social Care; for falls in the home £2 453 per case for NHS Primary, Secondary and Tertiary Care and £390 per case for Social Care and for common mental disorders £1 543 per case for NHS Primary, Secondary and Tertiary Care and non-NHS Social Care". Finally, GDP loss was "£682 per case of common mental disorders for those of working age" calculated using previous literature estimates (Stafford, 2015).

poisoning more than £168,500. These authors also estimated these costs across all homes in the UK, rather than only ethnic minorities. They estimated that excess cold costs the NHS more than £5 billion and that excess heat costs only £510,000. They further estimated that damp and mould cost the NHS more than £380 million, CO poisoning more than £7 million, and uncombusted fuel gas more than £3 million. However, the authors note that the calculations used to reach these estimates are subject to assumptions and so face a large margin of error (although they do not provide information on the margin of error).

The impact of new heating technologies and of energy efficiency interventions on indoor environment and health

This chapter will provide an overview of the literature identified relating to the impact of new heating technologies and energy efficiency interventions on the quality of the indoor environment and on health. As already laid out in the introduction, the search covered a range of different measures, including all the following:

- The improved energy efficiency of buildings, achieved mainly through:
    - Better insulation of walls, roofs, and window and door frames;
    - Controlled ventilation (often in combination with efficient heating systems);
    - Heat recovery; and
    - Double- or triple-glazed windows.
- New heating technologies (mostly relying on renewable energy sources), including:
    - Ground source heat pumps;
    - Solar water heating;
    - Other innovative heating technologies; and
    - Thermal stores.
- Improvements in combustion-based heating technologies, mainly improved boiler technologies.
- Greater energy-saving efforts by consumers through:
    - Increased general awareness of the cost- and environment-related implications of unnecessary heating and
    - Smart meters that help to track and monitor energy use.

Summary of the impacts of new heating technologies and of energy efficiency interventions

The results from the studies covering the impact of new and energy efficient heating interventions demonstrate the wide variety of health impacts and changes to the indoor environment of these technologies that have been measured in recent research. As the details of the various impacts of each type of energy efficient heating interventions can be difficult to identify across the literature sources, Table 4 and Table 5 provide an overview of the direction of impact for individual types of heating intervention (and whether these results were significant). This summary is broken down by the sub-research questions relating to this chapter.

What are the impacts of energy efficiency improvements (including combinations of interventions) on indoor air quality in homes and workplaces?
The evidence suggests that a range of indoor environmental factors are affected by new heating interventions. Although the vast majority of these showed positive or neutral effects, a small number showed worsening of the indoor environment.

In general, insulation was found to improve the indoor temperature. This finding concerns all types of insulation (although no information on significance is provided). The strongest evidence found with regard to external wall insulation (which was found to be significant). The research team found mixed evidence for the effects on humidity. Some studies found that insulation reduces humidity levels (although no information on significance is provided), whereas other found no association. Studies looking at mould found no association with cavity wall insulation. However, they found that loft insulation was significantly associated with higher levels of mould.

Mechanical ventilation was generally associated with lower levels humidity. A few studies investigating this link did not find an association. Significance information was not provided. One important and somewhat paradox finding is the fact that several studies found a significant association with greater levels of mould, despite lower humidity levels. Authors have speculated that this is a result of insufficient levels of ventilation because of inadequate functioning of the ventilation system. In addition, although mechanical ventilation was linked to a lower level of indoor contaminants (albeit no significance information provided), when combined with air tightness it was found to increase indoor radon levels unless introduced alongside heat recovery.

Studies assessing the impacts of multiple energy efficiency and new heating technologies together found multiple improvements. Significant improvements were seen with indoor temperature (including thermal comfort) and indoor pollution. This increase in temperature is particularly relevant given the negative health outcomes associated with living in a cold home, as outlined earlier in this report. Improvements, although with no significance information provided, were also seen in terms of levels of humidity, mould and damp. This may suggest that optimal improvements in air quality occur when multiple interventions are used in combination, as is also suggested by the reduction in radon when air tightness, mechanical ventilation and heat recovery are all used together.

How do different low carbon heating technologies impact on the indoor air quality of a property?
The research team found very limited information on low carbon heating technologies. The data on impacts that were available for low carbon technologies were not distinguished from those for other interventions (i.e. studies measured the impacts of multiple low carbon and

energy efficient interventions together). This means the specific impacts of low carbon technologies cannot be identified.

What are the impacts of installing specific energy efficiency measures (e.g. solid wall insulation, draught proofing and mechanical ventilation with heat recovery) on people's health?

As Table 5 shows, the reviewed literature assessed a wide range of health impacts after introduction of energy efficient heating systems. Although many studies show improvements in health outcomes, much of the evidence is mixed. Some health outcomes showing worsening effects after introduction of these systems.

Insulation, in general, was found to have a benefit for most health outcomes. No information on significance was found for any of these relationships. Insulation was found to reduce the risk of poor general physical health and mental health, asthma and wheeze. However, the higher temperatures caused by insulation were found to lead to higher risk of heat-related conditions during summer. In studies looking at specific types of insulation, wall insulation was found to significantly reduce the risk of emergency hospital admissions but had no association with falls. Similarly, no association was found between the presence of loft insulation and falls or hospital admissions. External wall insulation was found to improve respiratory health. No information on significance is provided.

Studies looking at mechanical ventilation found mixed results. Some studies found significant reduction in skin conditions, asthma and wheeze, although a small number found mechanical ventilation did not influence the risk of developing these conditions. The risk of lung cancer only reduced if mechanical ventilation was combined with heat recovery and air tightness, as this ensured the levels of indoor radon were low. When mechanical ventilation and airtightness were used without heat recovery, there was an increased risk of lung cancer as a result of greater radon.

Studies exploring the impacts of fabric works[61] also found mixed results. They found a lower risk of circulatory conditions and no association with allergies. No information on significance is provided. Mixed results were identified for headaches and mental health. Although some studies identified significant improvements in mental health and headaches, others found no association in this regard.

The majority of studies explored the health impacts of multiple energy efficiency improvements together, rather than individually. Significant improvements were seen with regards to general well-being and wheeze. Improvements (with no information on significance provided) were also detected in terms of lowering blood pressure and reduced risk of falls. Heat-related mortality was found to increase during summer. No significance information is provided. No association was found between multiple energy efficiency improvements and quality of life, bronchitis, circulatory conditions or ear infections. For other health outcomes, mixed evidence was found in the literature. Improvements were found for cold-related mortality, general physical and

[61] This involves external improvements to the home, including insulation, cladding and roof renewal.

mental health, respiratory health and asthma (significance was only provided for respiratory health and asthma). However, other studies exploring these health outcomes also found no associations. In addition, one study looking at asthma found significant worsening of certain asthma-related outcomes after the introduction of energy efficient systems.

Overall, this evidence suggests that energy efficiency measures lead to improvement for many health outcomes. In some cases, they do not influence the risk of developing health conditions, which can also be viewed as a positive outcome. Only a small number of studies found evidence of worsening health after introduction of energy efficient measures, and these effects could be mitigated by introducing complementary technologies to mitigate them (e.g. heat recovery alongside mechanical ventilation) and ensuring the systems are working correctly.

What are the impacts of moving to low carbon heating (e.g. heat pumps, fuel cells, hydrogen boilers and heat networks) on people’s health?

As was the case for the impacts of indoor air quality, there was very limited information on the impact of low carbon heating technologies. The data on impacts that was available for low carbon technologies was not distinguished from the impacts of other interventions (i.e. studies measured the impacts of multiple low-carbon and energy efficient interventions together). This means the specific impacts of low carbon technologies cannot be identified in this review.

Table 4: Summary of the impacts of new heating technologies and of energy efficiency interventions on the indoor environment

	Indoor temperature	Subjective indoor temperature	Humidity	Indoor pollution	Indoor radon	Mould	Damp
Insulation (general)	↑		↓				
External wall insulation	↑		↔				
Loft insulation						↑*	
Cavity wall insulation						↔	
Mechanical ventilation			↓ ↔	↓		↑*	
Airtightness					↑		
Airtightness + mechanical ventilation					↑		
Airtightness, mechanical ventilation + heat recovery					↓		
General/multiple energy efficiency improvements	↑*	↑*	↓	↓*		↑↓	↓

** Indicates that at least one study investigating this relationship found a statistically significant link.*

↑ *Indicates that the risk increases,* ↔ *indicates that there is no association and* ↓ *indicates that the risk decreases. Where two or more arrows are provided, this indicates mixed evidence in the literature.*

The row general/multiple energy improvements includes results from studies assessing multiple measures at one time. The other rows only include the results of studies that assess the impacts of single energy efficient measures, or distinguishes the impacts of different measures, rather than those that assessed the impacts of energy efficiency programmes or did not distinguish the effects of specific measures.

Table 5: Summary of the impacts of new heating technologies and of energy efficiency interventions on health

	Cold-related mortality	Heat-related mortality	Poor general physical health	Poor general mental health	Poor well-being	Quality of life	Hospital admissions	Poor general respiratory	Heat-related conditions	Asthma	Wheeze	Rhinitis	Bronchitis	Allergies	Lung cancer	Circulatory conditions	High blood pressure	Skin conditions	Falls	Headaches	Ear infections
Insulation (general)			↓	↓						↓	↓										
Wall insulation							↓*												↔		
Loft insulation							↔												↔		
External wall insulation								↓													
Mechanical ventilation										↓* ↔	↓↔	↓*↔						↓* ↔			
Fabric works				↓* ↔										↔		↓				↔	
Airtightness															↑						
Airtightness + mechanical ventilation															↑						
Airtightness, mechanical ventilation + heat recovery															↓						
General/multiple energy efficiency improvements	↓↔	↑	↓*↔	↓↔	↓*	↔	↓*↔	↓* ↔	↑	↓*↔↑*	↓*		↔			↓↔	↓		↓		↔

↑ Indicates that the risk increases, ↔ indicates that there is no association and ↓ indicates that the risk decreases. Where two or more arrows are provided, this indicates mixed evidence in the literature.

The row general/multiple energy improvements includes results from studies assessing multiple measures at one time. The other rows only include the results of studies that assess the impacts of single energy efficient measures, or distinguishes the impacts of different measures, rather than those that assessed the impacts of energy efficiency programmes or did not distinguish the effects of specific measures.

Introducing energy efficiency improvements can improve indoor temperature and humidity and reduce pollution

This section will outline the relevant results of the literature that reviewed the impact of introducing energy efficiency interventions on the indoor environment. The literature focused on the impacts on indoor temperature, humidity, pollution, and damp or mould.

Indoor temperature may increase after the introduction of energy efficiency improvements

Eight studies link various improvements related to insulation and energy efficiency to indoor temperature increases. A heating and insulation intervention resulted in homes that were warmer (Liddell & Guiney, 2015). The installation of a standard retrofit insulation package in another study led to a slight rise in bedroom temperatures during winter, of 0.5°C (Ige et al., 2018). Another paper reviewed by Ige et al. (2018) found that a combination of warmth and energy efficiency improvements was associated with a mean temperature increase in the living room of 1.10°C and in the child's bedroom of 0.57°C.[62] Installing external wall insulation increased temperature in a study conducted by Brown, Fattakhova, Bambra and Taylor (2017). No p-value is provided. Ambrose et al. (2018) found that introducing new boilers and insulation can increase the indoor temperature by 1.6°C. Willand et al. (2015), reviewing 13 studies published between 2002 to 2011, found that energy efficiency improvements resulted in rises in indoor temperature ranging from 0.6°C to 4.5°C, and, in one case, up to 7.1°C. National Energy Action provided a list of energy efficiency programmes run across the UK. A number of these had been evaluated and were shown to increase indoor temperatures. No p-values are provided for any of these (National Energy Action, 2015).

Poortinga et al. (2018) found that an energy efficiency and renewable heating programme (which included introduction of insulation, solar panels and heat pumps, among others) increased the indoor temperature on average by 0.84°C. Significant increases were seen in the living room and bedroom compared with control homes.[63] The number of heated rooms also increased in the intervention group, though not to a significant degree.[64] External wall insulation was the most effective improvement for increasing indoor temperature in this study.[65] The number of rooms heated during the evening did not significantly differ between control and intervention groups.[66] A new boiler or heater did not increase temperature to a significant level.[67] Finally, there was no impact on the period of time indoor temperatures remained below 18°C or 16°C between the intervention and control groups.[68]

[62] 95% CI 0.54° to 1.64°C for the living room and 95% CI 0.05° to 1.08°C for the child's bedroom.
[63] 95% CI 0.64° to 1.04°C. 95% CI 0.78° to 1.23°C for the living room and 1.04° to 1.52°C) for the bedroom.
[64] $p=0.055$.
[65] 1.12°C; 95% CI 0.69° to 1.55°C.
[66] $p=0.242$.
[67] −0.19°C; 95% CI −0.69° to 0.31°C.
[68] 0.27 hours; 95% CI −0.49 to 0.96 hours for below 18°C and 0.20 hours, 95% CI −0.48 to 0.88 hours for below 16°C.

Five studies assessing the impacts of energy efficiency programmes found improvements in subjective indoor temperature. Three of these reported significant results. Evaluations of several energy efficiency programmes showed improved client satisfaction with indoor temperature and a perception of warmer homes (no p-values provided) according to National Energy Action (National Energy Action, 2015). Similarly, Poortinga et al. (2018) found that participants in the intervention group had a significantly higher level of thermal satisfaction than those in the control group.[69] Stockton et al. (2018) found that an energy efficiency programme that involved the introduction of a range of different heating systems increased participants' perceived thermal comfort. In homes with two large energy efficiency measures,[70] thermal comfort significantly improved in 94% of respondents compared with 84% who had received only one large measure.[71] This suggests a combination of energy efficiency systems results in greater thermal comfort than introducing single measures. Bennett et al. (2016) evaluated the 'Warm at Home' programme, which includes introducing various energy efficiency measures. Participants reported an increase in their thermal comfort, increasing from 37% before the intervention to 73% after. No p-values were provided to demonstrate the significance of this relationship. The increase is almost two-fold, which indicates it would be statistically significant. Although this increase in temperature is likely to be favourable to health in winter, particularly in the UK climate, it may be detrimental in summer. For example, a study by Taylor et al. (2018) found that retrofitting homes with energy efficiency measures increased the indoor temperature during a warm summer by an average of 0.26°C (showing a range of −1.02°C to 1.72°C). This effect was found to be worse during the 2013 ten-day heatwave in the UK, when retrofitted homes experienced an increase in temperature of 0.4°C (showing a range of −0.61°C to 1.61°C). The potential health impacts of this will be discussed later in this chapter.

Energy efficiency interventions can reduce humidity levels indoors
Several studies found that insulation, mechanical ventilation, and energy efficiency improvements lower humidity levels.

A literature review found that the installation of a standard retrofit insulation package resulted in a decrease in relative humidity of −2.3% (Ige et al., 2018). Two other literature reviews noted that a combination of heating and insulation resulted in homes that were drier (Liddell & Guiney, 2015). In addition, three studies cited in a review by Krieger et al. (2010) observed that the installation of whole-house mechanical ventilation can decrease humidity, although the finding was described as requiring more field evaluation.

Seven of the 28 energy efficiency improvement programmes reviewed by Willand et al. (2015) showed that an increase in indoor temperatures would lower average relative humidity level. Given this finding, the authors searched for any implications on mould growth. They did not find conclusive evidence that lower humidity levels would have any effect on mould. In general,

[69] p=0.000.
[70] Large energy efficiency measures were one or more of loft, cavity wall or solid wall insulation, heating system replacements, heat pumps, advanced heating controls and ventilation.
[71] p=0.042.

studies on intervention programmes across all categories investigated in Willand et al. (2015) reported a decrease in reported problems with mould. Five studies reported conflicting findings or new mould in some of the participating homes. Here, inadequate ventilation was suspected as the confounding factor.

Bennett et al. (2016) noted that home satisfaction relating to humidity increased with energy efficiency improvements, with 49% being satisfied with the humidity levels before interventions versus 71% afterwards. No p-value is provided. The study does not distinguish between the effects specifically as a result of the introduction of energy efficiency measures compared with other aspects of the programme.

In contrast, Poortinga et al. (2018) found energy efficiency interventions do not have a significant impact on changing humidity levels.[72] External wall insulation, which included the installation of mechanical ventilation, did not increase levels of indoor relative humidity, nor did the installation of boilers or heating systems.[73] Although connecting to a gas network led to a slight increase in indoor humidity, this was not significant.[74] However, the authors did find that the intervention reduced the duration of indoor humidity levels of greater than 60% by 1.14 hours (no p-values provided).[75]

Energy efficiency improvements can reduce indoor air pollution, although this depends on the type of pollution and heating system

Studies show how energy efficiency improvements can decrease indoor environmental contaminants.

Three studies cited in a literature review by Krieger et al. (2010) found that the installation of whole-house mechanical ventilation can decrease indoor contaminants, assuming that the outdoor air has lower levels of contaminants than the indoor air, and also can reduce allergen levels. The authors described these findings as promising but requiring more field evaluation. Another literature review found that a combination of warmth and energy efficiency improvements led to lower levels of NO_2 in the living rooms of intervention households than in those of the control households.[76] A similar effect was found in children's bedrooms of these households (Ige et al., 2018).[77]

Only one study found inconclusive evidence that ventilation technology, specifically increasing the ventilation rate, could decrease the indoor NO_2 concentration, citing that the pollutant has both indoor (e.g. gas cooking) and outdoor (e.g. motor vehicles) sources contributing to the overall levels inside homes (Sundell et al., 2011).

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72 95% CI −0.74% to 0.83% RH.

73 −0.60%, 95% CI −2.26% to 1.06% for mechanical ventilation and −1.59%, 95% CI −3.52% to −0.34% for installation of boilers and heating system.

74 3.86%, 95% CI 2.31% to 5.41%.

75 95% CI −2.00 to −0.28 hours.

76 Geometric mean 8.5 µg/m3 versus 15.7 µg/m3, p <0.001.

77 Geometric mean 7.3 µg/m3 versus 10.9 µg/m3, p=<0.001.

One study found that radon levels increase indoors after the introduction of air tightness, with or without mechanical ventilation (Milner et al., 2014). These authors modelled the impact on homes after making homes airtight and then introducing mechanical ventilation and heat recovery. It was found that making homes airtight alone increases the levels of indoor radon by 57%. Although the average level the radon reached was still below the PHE recommended maximum indoor level, some homes in the model did exceed this level. Furthermore, if there were to be an increase of 0.6% to 2% in homes above this limit in the UK (as the model suggests may happen), this would lead to an additional 750,000 individuals living in homes with radon levels above the recommended limit. Although introducing mechanical ventilation alongside making homes airtight was found to reduce this higher radon level, the modelled levels were still estimated to be higher than those of the present day. However, if heat recovery systems are put in place alongside mechanical ventilation and airtightness and these systems are all functional, the indoor radon levels are reduced to below present-day levels.

Different types of insulation result in varying impacts on mould and damp development

Although the evidence suggests that energy efficiency improvements can reduce humidity, some studies identified mixed results on mould growth and damp after the introduction of ventilation and insulation or of various energy efficiency measures together.

Five studies reported evaluation results of energy efficiency programmes to assess the impact on damp and condensation. Both Brown et al. (2017) and National Energy Action (2015) found evidence of energy efficiency programmes reducing damp. No assessments of significance are provided in either publication. Ambrose et al. (2018) noted that energy efficient heating systems can help to reduce damp and mould through increasing indoor temperatures, ventilation and water tightness of homes. No p-values are provided. An evaluation of an energy efficiency programme by Stockton et al. (2018) found that 42% of homes with small energy efficiency measures put in place reported improvements in damp and condensation, which, the authors speculate, was the result of ventilation. However, this causal link was not investigated by the authors and no p-values are provided. Bennett et al. (2016) reported improvements in damp and condensation after the introduction of an energy efficiency programme. Before the intervention, 48% of participants reported that their home was damp and 57% reported condensation. After the intervention, this dropped to 32% for damp and 34% for condensation. No p-values were provided to demonstrate the significance of this reduction.

One paper explored the impact of insulation alone, rather than a combination of measures, on the development of mould. Sharpe, Thornton, Nikolaou, & Osborne (2015a) identified that insulation was found to either worsen mould growth or have no effect, depending on the type of insulation. The authors identified that homes with wall or loft insulation installed five or more years ago were not significantly more likely to have mould growth than those with insulation less than five years old.[78] Homes with loft insulation were found to have significantly higher levels of mould, yet cavity wall insulation had no significant impact on mould growth.[79]

One study looking at ventilation alone, rather than ventilation in combination with other interventions found an increase in mould contamination. The use of kitchen and bathroom extractor fans alone in homes was found to significantly increase visible mould and mouldy or musty odour.[80] The authors speculate that this may be because of ineffective functioning of the extractor fan system, meaning dampness is not removed effectively. The authors suggest that mechanical ventilation systems should be introduced alongside other systems to help reduce dampness (Sharpe et al., 2015a). Ventilation was also thought to play a role in the conflicting findings in a literature review conducted by Willand et al. (2015). Although this study found a decrease in mould across energy efficiency programmes, five studies reviewed by the authors found inconclusive evidence or reports of new mould development, which was thought to be a result of inadequate ventilation systems. This links back to the importance of having functioning energy efficient heating systems, as discussed previously.

Although an assumption could be made that introducing energy efficiency improvements into the home may mitigate some effects of fuel poverty, the two studies by Sharpe and colleagues found mixed results. When looking at the presence of visible mould or mouldy or musty odours, the authors found that using mechanical ventilation did not significantly mitigate the effects of fuel poverty behaviours, such as not using heating because of cost (Sharpe et al., 2015a).[81] However, when looking at the effects of highly energy efficient homes more generally (indicated by high SAP ratings), they found those with higher ratings had a significant reduction in visible mould growth and mouldy or musty odours.[82] This effect was not mitigated when taking into account fuel poverty behaviours (Sharpe et al., 2015a).[83] Sharpe et al. (2015b) found this same result but provided more detail on the effects of different SAP ratings. A per unit increase in SAP rating resulted in a significant reduction in mould growth and mould or musty odours.[84] Higher SAP ratings had a stronger association with a reduction in visible mould and odours. Homes with SAP ratings above 71 (indicating high energy efficiency) had a significant reduction in visible mould.[85] The reduction was not significant for homes rated 64 to 71. Homes with SAP ratings of 65 to 71 and 71 and above had significant reductions in mouldy or musty odours, although those rated 60 to 65 did not.[86]

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[78] p=<0.01.
[79] 95% CI 1.7 to 5.4, p=<0.001 for loft insulation and 95% CI 0.4 to 0.9 for cavity wall insulation.
[80] 95% CI 0.173 to 0.803, p=0.001 for visible mould and 95% CI 0.069 to 0.293, p=0.001 for odours.
[81] 95% CI 0.389 to 0.988, p=0.000 for visible mould and 95% CI 0.169 to 0.383, p=0.000 for odours.
[82] 95% CI 0.376 to 0.982, p=0.000 for visible mould and 95% CI 0.539 to 1.280, p=0.000 for odours.
[83] 96% CI −0.035 to 0.009, p=0.001 for visible mould and 95% CI −0.030 to −0.002, p=0.030 for odours.
[84] OR 0.95, 95% CI 0.93 to 0.99, p=0.001 to 0.01 for visible mould and OR 0.96, 95% CI 0.93 to 0.99, p=0.001 to 0.01 for odours.
[85] OR 0.4, 95% CI 0.2 to 0.7, p=0.001 to 0.01.
[86] OR 0.9, 95% CI 0.4 to 1.8, 95% CI <0.001 for SAP ratings 65 to 71 and OR 0.3, 95% CI 0.1 to 0.7 for SAP ratings 71 and over.

The health impacts of introducing energy efficiency improvements are mixed, although the trend suggests some health improvements

Earlier in this report, it was discussed that individuals living in homes with poor heating, cooking and ventilation systems are likely to have poorer health outcomes. This section will outline the results of the literature reviewed on how energy efficient heating, cooking and ventilation systems can impact on health. It will cover the health impacts on general health and well-being, respiratory conditions, cardiovascular conditions, mental health outcomes and other health conditions (which include skin conditions, ear infections, falls or injuries and headaches).

Improved energy efficiency may reduce mortality and improve general health and well-being, although certain factors can prevent these improvements from occurring

Many of the studies reviewed explored the impacts of energy efficiency improvements on general health outcomes, including mortality, general physical health, hospital admissions and well-being. Although the majority of these studies found a positive association between general health and energy efficiency improvements, some did not find any association and one identified a negative impact on heat-related mortality linked to energy efficiency interventions.

Cold-related mortality can be reduced by introducing energy efficiency improvements, although that may contribute to an increase in heat-related mortality

Three studies conducted in the UK explored the link between energy efficiency improvements in the home and mortality.

Ambrose et al. (2018) found that energy efficiency improvements increased the indoor temperature, which contributed to a reduction in excess winter deaths. Similarly, Tammes et al. (2018) found that the risk of mortality during a three-day period of low outdoor temperatures was not significantly different when comparing homes that were energy efficient and those that were less energy efficient. The reason for this was not discussed in the paper.[87]

This positive impact was not seen when looking at heat-related mortality in one UK study. Taylor et al. (2018) modelled the impact of retrofitting UK homes on mortality and found that retrofitting increased the number of heat-related deaths by 14% during average summer temperatures and by 1% during the 2010 summer heatwave compared with homes that had not been retrofitted. However, the authors note that this increase in summer mortality is likely to be outweighed by the reduction in cold-related deaths seen during winter. The authors did not provide information on why heatwaves deaths are lower than average summer deaths. It may be because heatwaves tend to last for a shorter period of time, although this possibility is not discussed by the authors.

[87] p=>0.5.

General physical health appears to improve after the introduction of energy efficiency improvements, although some evidence suggests no association

Many studies investigated the association between general health outcomes and energy efficiency heating improvements in the home. The majority of these studies found positive health outcomes, although a small number found no association. None of the studies reviewed found a negative impact on general health outcomes.

Four studies found an association between positive health outcomes and general energy efficient heating systems. Either the exact systems implemented were not specified or multiple interventions were introduced together. For example, Stockton, Ruse, Garrett, Garlick, and Powells (2018) found that 36% of participants in the UK's 'Health and Innovation Programme'[88] reported improvements in their physical health. No p-value is provided. In addition, these authors found that, as thermal comfort increased, there was a significant increase in participants' positive perceptions of physical and mental health.[89] Similarly, National Energy Action provided a list of health-related fuel poverty schemes in the UK and highlighted how evaluations of five of these demonstrated health improvements. However, no further details on the type of improvement or the statistical significance of these relationships are provided (National Energy Action, 2015).

Some studies found that vulnerable households, in particular, benefitted from energy efficiency improvements. Bennett, Dayson, Eadson, Gilbertson, and Tod (2016) found that participants in England's 'Warm at Home' programme, which supplies vulnerable homes with energy efficient heating systems, reported improvements in their health. The proportion of participants reporting very bad health dropped from 49% to 42% after the intervention was introduced. No p-values are provided. Similarly, an evaluation of the 'Affordable Warmth for Disabled Households' scheme in Coventry, the UK, was found to improve participants health and reduced the number of GP visits and hospital admissions (National Energy Action, 2015). No p-values are provided. A review of the impacts of energy efficiency improvements found that low-income study participants experienced significantly greater health benefits than the general population. The same effect was seen when looking at the impacts for children (Maidment et al., 2014).[90] These authors speculate that these positive effects are seen in low-income individuals because they are often starting at a lower baseline in terms of their housing quality and/or health, which means there is a greater scope for improvement.

One report explored the health impacts specifically as a result of introducing insulation (Public Health England et al., 2014). These authors reported that insulating homes can reduce heat absorption, protecting the home from high outdoor temperatures. They suggest this has a beneficial effect on physical and mental health. They also suggest that external wall insulation may have greater impacts than internal wall insulation because it prevents heat from entering

[88] This programme involves the introduction of a number of energy efficiency measures, including heating systems (new systems and repairs/improvements to existing ones), insulation, heating control, draught proofing, battery storage and/or solar, and ventilation.

[89] $p=<0.001$ for both small and large energy efficiency interventions.

[90] $d=0.08$, 95% CI -0.01 to 0.18, $p=<0.05$ for the general population and $d=0.08$ for children.

the home. They also suggest that insulation is most effective at keeping indoor temperatures lower during high outdoor temperatures when combined with other interventions, such as window shutters or white curtains. However, the authors do not provide a reference to the source of this evidence and they provide no information on significance (Public Health England et al., 2014).

Despite this evidence suggesting that introducing energy efficiency interventions improves health outcomes, three studies found no statistical association. A literature review by Willand, Ridley, and Maller (2015) of energy efficiency interventions identified eight studies that found inconclusive evidence of the link to various health improvements. However, the review did identify studies that found a positive health impact when looking at specific health outcomes, including respiratory and cardiovascular conditions (discussed later in this section). Two studies explored the impact of energy efficiency programmes and found no link to health improvements. Although Stockton et al. (2018) found that 36% of the ‘Health and Innovation Programme’ participants reported improved health outcomes, an additional 56% reported that their health had remained the same after the interventions were introduced. No p-value is provided. Similarly, Grey et al. (2017) explored the impact on the health of those living in fuel poverty homes with energy efficiency schemes in Wales, which included external wall insulation, central heating upgrades and connection to gas networks. The authors found no statistically significant difference in physical health outcomes compared with the control group.[91]

The impact on hospital admissions after the introduction of energy efficiency improvements varies by the type of system and the age of individuals

Two studies exploring the link between energy efficiency improvements and hospital admission found mixed results depending on the type of intervention and age of participants.

Rodgers et al. (2018) explored the health impacts of increasing housing standards in Wales, with a focus on the impacts of introducing loft and wall insulation. These authors found that wall insulation had a positive impact on reducing hospital admissions, whereas loft insulation had no impact. Elderly patients from dwellings with wall insulation were found to have a statistically significantly lower risk of being admitted to hospital in an emergency than the control group.[92] The same effect was seen when looking at all age groups for emergency admissions.[93] This relationship was not seen with loft insulation, which had no significant association with emergency hospital admissions for any age group.[94] Although the reason for these associations are not directly investigated in this study, the authors speculate that the reduction in hospital admissions may be because of increased indoor temperatures having reduced the level of damp and mould, reducing the risk of developing respiratory conditions.

[91] p=0.145.
[92] IRR 0.75, 95% CI 0.64 to 0.83, p=<0.01.
[93] IRR 0.80, 95% CI 0.73 to 0.87, p=<0.01.
[94] IRR 0.92, 95% CI 0.85 to 1.01, p=0.083 for all age groups and IRR 0.98, 95% CI 0.86 to 1.11, p=0.695 for elderly participants.

Higher indoor temperatures may also contribute to a lower risk of developing circulatory conditions.

Poortinga et al. (2018) explored a similar relationship to Rodgers and colleagues (2018), exploring the impacts on hospital admissions of the ‘Arbed’ programme. This programme involves the introduction of various heating and energy efficiency improvements in the households of low socioeconomic status in Wales: retrofitting of solid wall insulation, solar panels, solar hot water, heat pumps, boiler upgrades and replacements, as well as heating system upgrades, such as gas combination boilers and connecting to the mains gas network. This study found that the ‘Arbed’ programme had a positive impact on reducing emergency cardiovascular-related hospital admissions in elderly participants but that this effect was not seen when looking at all age groups.[95] However, there was no association between respiratory-related emergency admissions between those in the ‘Arbed’ programme in any age group, including the elderly.[96] The reason for this association was not discussed in this study.

Households with energy efficiency improvements appear to report improvements in their subjective well-being

Four studies explored the impact of energy efficiency improvements on well-being. Three of these identified positive well-being outcomes and the other found mixed outcomes.

Bennett et al. (2016) explored the effects of England’s ‘Warm at Home’ programme, which supplied vulnerable homes with heating and energy efficiency upgrades. This study found that the proportion of participants reporting low well-being dropped from 39% to 24% when large energy efficiency interventions were introduced and from 35% to 27% for smaller interventions. No p-value is provided. Similarly, Grey et al. (2017) found a statistically significant improvement in subjective well-being in an intervention group who received energy efficiency measures in Wales (including external wall insulation, central heating upgrades and connection to gas networks) compared with the control group.[97] These authors suggest this improvement in well-being may be because of greater satisfaction with housing quality and temperature, and lower energy bills. Participants in the ‘Arbed’ programme were found to have significant improvements in subjective well-being compared with the control group (Poortinga et al., 2018).[98] Finally, participants of the ‘Health and Innovation Programme’ reported significant improvements in well-being, which included measures of cheerfulness, relaxation, optimism and interest in new things.[99] Households reporting an increase in thermal comfort were significantly more likely to feel improvements in well-being compared with those who did not (Stockton et al., 2018).[100]

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[95] $p=0.009$; 95% CI 0.0068 to 0.0479 for elderly participants and $p=0.694$; 95% CI −0.0083 to 0.0055 for all age groups.
[96] $p=0.348$; 95% CI −0.0046 to 0.0131 for all age groups and $p=0.144$; 95% CI −0.0141 to 0.0964 for those aged 60 and above.
[97] $p=0.004$.
[98] $p=0.004$.
[99] $p=0.01$.
[100] $p=<0.001$ for relaxation and $p=<0.01$ for other measures.

Although Poortinga et al. (2018) found improvements in subjective well-being as a result of participating in the 'Arbed' programme, the same was not seen for quality of life. No difference between the intervention and control groups was found when looking at the physical quality of life or quality-adjusted life years (QUALYs).[101]

The impact on respiratory health after the introduction of energy efficiency improvements is mixed, with evidence showing benefits, no impact and negative outcomes

Many studies reviewed explored the link between respiratory conditions and energy efficiency interventions, including general respiratory health, asthma, and other respiratory conditions. The results of these outcomes were very mixed across positive, neutral and negative outcomes.

Studies exploring the impacts of energy efficiency interventions on general respiratory health found both positive health impacts and no associations

Nine studies explored the general respiratory outcomes in homes with energy efficiency interventions. The results of these studies were mixed, with some finding positive outcomes and some no impact on respiratory outcomes. None found a negative impact on health. The majority of these explored the impacts of a variety of interventions together, rather than individual interventions. In those studies that found improvements in respiratory health, this was often linked to the reduction in damp and mould as a result of higher indoor temperatures.

One literature review of the impacts of energy efficiency improvements identified ten studies that found improvements in respiratory health and eight studies that did not find an association (Willand et al., 2015). For the studies that found improvements in respiratory health, the authors propose that this is a result of energy efficiency improvements leading to increased indoor temperatures, which lowers the risk of homes developing damp and mould. A meta-analysis found that those with existing respiratory diseases living in homes with energy efficiency interventions experienced significant health benefits.[102] However, this improvement was significantly lower[103] than that seen in those with other existing conditions (skin conditions, ear infections and high blood pressure) (Maidment et al. 2014). Two studies conducted in the UK identified that energy efficiency improvements can reduce the incidence of damp and mould, which was linked to improvements in respiratory health in both studies. Brown, Fattakhova, Bambra, and Taylor (2017) found that external wall insulation introduced into households of low socioeconomic status led to a reduced risk of respiratory conditions, which they linked to higher indoor temperatures and less mould. Similarly, Ambrose et al. (2018) found that energy efficiency improvements helped to alleviate respiratory conditions in children, which they also linked to a reduction in damp and mould.

[101] $p=0.145$ for physical quality of life and $B\ -0.007$, 95% CI -0.04 to 0.02 for QUALYs.
[102] $d=0.07$, $p=<0.01$.
[103] $p=0.001$.

Other studies that were reviewed found no association between these. Two of these were literature reviews. One review found no impact on respiratory outcomes other than asthma, wheeze and bronchitis as a result of warmth and energy efficiency improvements in the homes of children and adults from the UK (Thomson, Thomas, Sellstrom, and Petticrew, 2013).[104] Similarly, the other review, by Willand et al. (2015), found that 8 of the 13 studies the authors reviewed that explored the impacts of low carbon refurbishment and mechanical ventilation found no impact on respiratory health, although 3 reported improvements.

Three papers explored the impact of UK schemes that introduced energy efficiency improvements into homes and found they had no impact on respiratory outcomes. Grey et al. (2017) found that energy efficiency interventions introduced in Welsh homes classed as being in fuel poverty had no statistically significant difference in respiratory symptoms compared with the control group.[105] Similar results were found when evaluating the 'Arbed' programme. There was not a significant difference when looking at respiratory symptoms between the intervention and control group.[106] Finally, participants of the 'GoWell' project in Glasgow, which includes the introduction of fabric works, were found to have improvements in the recovery from respiratory outcomes[107] and the development of respiratory conditions. These were not significantly different from the control group.

The effects on asthma after the introduction of energy efficiency improvements are also very mixed, with some evidence suggesting a worsening of asthma outcomes

Many of the studies reviewed explore the impact of energy efficiency interventions on asthma. As with general respiratory outcomes, the results of these studies are very mixed and include some negative outcomes.

Multiple studies found positive outcomes for asthma. A systematic review conducted by Ige et al. (2018) explored the asthma outcomes for a range of populations and energy efficiency interventions. One paper these authors reviewed found that asthmatic children from New Zealand living in homes with warmth and energy efficient improvements had fewer reports of poor health, less sleep disturbed by wheezing, less dry cough at night, and reduced scores for lower respiratory tract symptoms than children in the control group (Ige et al., 2018).[108] Similarly, another paper included in this review found that intervention improved parent-reported childhood asthma in asthmatic children at 4 and 12 months old (Ige et al., 2018).[109] When looking at adult asthma outcomes, the review identified a paper that found UK adults living in homes with improved ventilation, heating and insulation showed an improved combined asthma symptom score, although this was not significant (Ige et al., 2018).[110] Finally,

[104] OR 1.01, p=0.97.
[105] p=0.485.
[106] p=0.485.
[107] p=>0.05, OR 0.95, 95% CI 0.46 to 1.95.
[108] aOR 0.48, 95% CI 0.31 to 0.74 for reports of poor health; 95% CI 0.55, 0.35 to 0.85 for less sleep disturbed by wheezing; 95% CI 0.52, 0.32 to 0.83 for less dry cough at night; and 95% CI 0.77, 0.73 to 0.81 for reduced scores for lower respiratory tract symptoms.
[109] 95% CI 2.8 to 11.4, p=0.001.
[110] p=0.07.

another paper included in this systematic review found significant improvements for both adults and children from low-income homes in New Zealand with energy retrofits and insulation for self-rated health and wheezing (Ige et al., 2018).[111] A study exploring the impacts of mechanical ventilation found significant improvements in evening peak flow for asthmatics with dust mite allergies.[112] However, it found no impact on other asthma measures (discussed in the following section) (Singh & Jaiswal, 2013). Finally, another literature review suggested that the link between asthma improvements and energy efficiency improvements is the reduction in damp and mould in homes (Krieger et al., 2010).

Many other studies reported no impact, and one reported a worsening of asthma outcomes. A literature review by Fisk (2018) found no significant differences in improved asthma symptoms in asthmatic patients with the introduction of mechanical ventilation (Fisk, 2018). No p-value is provided. Grey et al. (2017) and Sharpe, Thornton, Nikolaou, and Osborne (2015b) also explored asthma outcomes after introducing various energy efficiency improvements in the UK and found no association. Grey et al. (2017) found that those in an intervention group whose homes received external wall insulation, central heating upgrades and connection to gas networks in Wales had no statistically significant difference in asthma symptoms compared with the control group.[113] Sharpe et al. (2015b) found that a unit increase in the energy efficiency of UK homes with visible mould was not significantly associated with adults taking asthma medication when looking across different ratings of energy efficiency ratings.[114] As discussed earlier in this section, Singh and Jaiswal (2013) explored the impacts on asthma outcomes specifically as a result of introducing mechanical ventilation. Although they found a significant improvement in peak flow rate in asthmatics with dust mite allergies, they found no association between mechanical ventilation and morning peak flow, quality of life, requirement for rescue medication, requirement for oral corticosteroids, visits to the GP or exacerbation needing emergency department visit or hospitalisations.[115] Similarly, a review of warmth and energy efficiency improvements found that children and adults from the UK did not show any relationship between asthma outcomes and presence of the improvements compared with the control population (Thomson et al., 2013).[116]

Although Sharpe et al. (2015b) found no link between the need for asthma medication and energy efficiency improvements, they did find a negative impact on other asthma outcomes. They found a significant association between a per unit increase in the energy efficiency of homes and a higher risk of an adult seeing a doctor for asthma in the previous 12 months.[117]

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[111] aOR 0.50, 95% CI 0.38 to 0.68 for self-rated health and aOR 0.57, 95% CI 0.47 to 0.70 for wheezing.
[112] MD 24.56, 95% CI 8.97 to 40.15.
[113] p=0.600.
[114] OR 1.02, 95% CI 0.99 to 1.05.
[115] MD 13.59, 95% CI 2.66 to 29.84 for dust mite allergy; MD −2.83, 95% CI −7.82 to 2.16 for quality of life; OR 0.52, 95% CI 0.22 to 1.24 for rescue medication; OR 0.52, 95% CI 0.22 to 1.24 for requirement for oral corticosteroids; OR 0.29, 95% CI 0.01 to 7.28 for visits to the GP; OR 1.84, 95% CI 0.32 to 10.52 for exacerbation needing emergency department visit; OR 0.09, 95% CI 0 to 1.72 for exacerbations needing hospitalisations.
[116] OR 0.95, p=0.81.
[117] OR 1.03, 95% CI 1.00 to 1.06, p=<0.01 to 0.05.

This effect was found to be stronger in homes classed as very energy efficient (SAP levels above 71).[118] The results were not significant for lower rated homes (scoring 24 to 71). However, this study also found that more energy efficient homes, demonstrated by improved insulation, resulted in a reduction in mould growth, meaning the link between energy efficiency and asthma is unclear. However, the authors speculate that it may be that, although insulation has improved, ventilation is still insufficient. This means that allergens and pollutants, particularly volatile organic compounds, are still present in the home and are risk factors for asthma exacerbation (Sharpe et al., 2015b).

The results for other respiratory outcomes after the introduction of energy efficiency improvements are very mixed

A small number of studies explored the impact of energy efficiency interventions on respiratory outcomes other than asthma, including wheeze, rhinitis, bronchitis, allergies and lung cancer. These studies also showed mixed evidence as to the direction of impact.

Two reviews identified studies that explored the impact of energy efficiency interventions on wheeze outcomes. A paper reviewed by Thomson et al. (2013) found that wheeze in the past three months in children and adults from New Zealand was significantly reduced for those with warmth and energy efficiency improvements at home.[119] Other health impacts caused by wheezing were also found to be reduced in children, including sleep disturbed by wheeze, speech disturbed by wheeze, dry cough at night, and wheeze during exercise (Thomson, Thomas, Sellstrom, & Petticrew, 2013).[120] These authors do not provide detail on what might be the cause of improvements in wheeze. When looking specifically at the effects of mechanical ventilation, a paper reviewed by Fisk (2018) found that this was associated with a 12% reduction in wheeze per week over 12 weeks in asthmatic children compared with the control group without mechanical ventilation (Fisk, 2018). No p-value is provided. However, another paper reviewed by Fisk (2018) found no association between wheeze in asthmatic children and mechanical ventilation. This author speculates that the reduction in wheeze may be a result of a reduction in dampness in the home. However, they note that many of the studies they reviewed do not control the results for dampness and that it is thus difficult to definitively make this conclusion.

Fisk (2018) also reviewed studies that explored the link between mechanical ventilation and rhinitis. The majority found no association between the two. One study found a significant improvement in rhinitis outcomes when bedroom ventilation improved.[121] However, eight other studies did not find a significant association.

One review identified a paper investigating the link between bronchitis in children from New Zealand and warmth and energy efficiency improvements. This paper found no significant

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[118] OR 2.9, 95% CI 1.4 to 6.0, $p=0.001$ to 0.01.
[119] OR 0.57, $p=<0.00001$
[120] OR 0.56, $p=<0.01$ for wheeze; OR 0.59, $p=0.005$ for speech disturbed by wheeze; OR 0.52, $p=0.008$ for dry cough at night; and OR 0.67, $p=0.09$ for wheeze during exercise.
[121] $p=0.023$.

difference in bronchitis between children in homes with energy efficient improvements and those without (Thomson et al., 2013).[122]

One paper explored the link between allergies and fabric works in Glasgow homes that were part of the 'GoWell' project (Curl & Kearns, 2015). These authors found no significant difference between the introduction of fabric works and the development of allergies.[123]

Finally, one paper modelled the impact of introducing mechanical ventilation and making homes airtight on lung cancer risk as a result of the presence of indoor radon in the UK, which was discussed earlier in this chapter (Milner et al., 2014). These authors found that if homes are made airtight or are made airtight and also have mechanical ventilation, there is an increased risk of developing lung cancer as a result of higher levels of indoor radon. Air tightness alone was found to increase the attributable burden of lung cancer mortality by a peak of 4,700 lost years and 278 additional deaths per year in the UK. The authors modelled what this could lead to 100 years after making homes airtight and found 367,200 fewer life years would be lived by the UK population. Because of the time lag between radon exposure and lung cancer development, these impacts would take around 10 years to start appearing. The authors also looked at the impact of introducing mechanical ventilation alongside air tightness and found that this still led to an increase in lung cancer burden but less so than air tightness alone, resulting in around 100 additional deaths in the UK per year. The authors' model suggests that younger people exposed to radon are more at risk of developing lung cancer. When mechanical ventilation and airtightness were introduced alongside heat recovery systems, the model showed a reduction in lung cancer cases, although the model also shows the importance of these systems functioning correctly to ensure this positive impact is maintained (Milner et al., 2014).

Cardiovascular health appears to improve after the introduction of energy efficiency improvements

Four studies explored the impact of energy efficiency interventions on circulatory health. Three found a positive health impact and one found no association.

Willand et al. (2015) conducted a literature review into the impacts of energy efficiency improvements. All four studies the authors identified exploring the effects on cardiovascular health reported subjective or objective improvements. No p-value is provided. As previously discussed, these authors suggest this is a result of higher indoor temperatures, which reduce the development of damp and mould. This is thought to contribute to a lower risk of cardiovascular conditions. Similarly, a review by Maidment et al. (2014) found that energy efficiency improvements were linked to lower blood pressure. No p-value is provided. As discussed previously, this may be because the focus of this study was on low-income individuals, who begin with a lower baseline for housing quality and/or health and so have a greater scope for improvement. Ambrose et al. (2018) reported that the elderly may benefit

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[122] OR 1.01, p=0.99.
[123] OR 0.52 to 1.38.

most from energy efficient improvements with regards to cardiovascular health as the increased indoor temperature can help to alleviate existing health problems. No p-value is provided. This reason for this improvement is not discussed in this study.

One study found no association between energy efficiency improvements and cardiovascular outcomes. Curl and Kearns (2015) found that the introduction of fabric works in Glasgow homes as part of the ‘GoWell’ project resulted in a slight improvement in the recovery from circulatory conditions and in the prevention of the development of circulatory conditions, but neither of these were significant relationships.[124]

The evidence for mental health outcomes after the introduction of energy efficiency improvements is very mixed

Multiple studies reviewed explored the impact of energy efficiency interventions on mental health outcomes and found mixed evidence. None of the studies reviewed found evidence suggesting mental health worsened.

Three studies found improvements in mental health outcomes as a result of introducing energy efficiency interventions. Liddell and Guiney (2015) conducted a literature review and found that significant improvements in mental health were seen in 64% of the studies they reviewed after energy efficiency improvements were introduced. These authors also identified a paper that explored the mental health impacts on adults and children in low-income homes in New Zealand and found evidence that those living in with energy efficiency improvements showed significantly lower odds of being classed as having poor mental health (Liddell & Guiney, 2015). These authors hypothesise that these improvements in mental health are the result of lower fuel bills (and thus lower risk of fuel poverty) and improved thermal comfort leading to lower stress levels. An evaluation of the ‘Health and Innovation Programme’ found that 35% of respondents showed improved mental health after the introduction of energy efficiency measures (Stockton et al., 2018). No p-value is provided. Similarly, Curl and Kearns (2015) found that homes participating in the ‘GoWell’ project in Glasgow were significantly more likely to recover from existing mental health conditions after the introduction of fabric works, possibly because of greater thermal satisfaction.[125]

Other studies did not find an association between mental health outcomes and energy efficiency interventions. Although Curl and Kearns (2015) identified significant improvements in the recovery from mental health conditions after the installation of fabric works, they found no association found for the onset of mental health conditions (OR 0.34 to 1.21). Similarly, although Liddell and Guiney (2015) identified some improvements in mental health outcomes as a result of energy efficiency interventions in general, they found no association when looking individually at insulation or better ventilation. No p-value is provided. Grey et al. (2017) found that homes classed as being in fuel poverty in Wales that received energy efficiency measures, including insulation and connection to gas networks, had no significant difference in

[124] $p=>0.05$, OR 1.60, 95% CI 0.85 to 2.98 for recovery and OR 0.85 to 1.68 for development of the conditions.
[125] OR 3.55, 95% CI 1.03 to 12.23, $p=<0.05$.

mental health outcomes compared with the control group.[126] An evaluation of the 'Arbed' programme found no significant difference between the control and intervention groups when looking at mental health conditions (Poortinga et al., 2018).[127] Finally, although the evaluation of the 'Health and Innovation Programme' found improvement in the mental health of some participants, 61% reported that their mental health had not changed after the programme was implemented (Stockton et al., 2018). No p-value is provided.

In general, the evidence on links between energy efficiency improvements and other health aspects (including skin conditions, ear infections, falls and headaches) is mixed or weak

Five papers explored the effects of energy efficiency interventions on other health outcomes, including skin conditions, ear infections, falls and injuries, and headaches.

A literature review by Fisk (2018) found mixed evidence as to the impact of mechanical ventilation on skin conditions. One paper the authors reviewed found significant improvements in skin conditions.[128] However, five other studies the authors reviewed found no association. A meta-analysis by Maidment et al. (2014) found improvements in skin conditions. No p-value is provided. Neither of these studies suggest why improvements in skin conditions might be seen after the introduction of mechanical ventilation.

One meta-analysis explored the impact on ear infections of energy efficiency improvements and found improvements, but it did not provide a reason as to why this improvement was seen (Maidment et al., 2014). No p-value is provided.

Two studies found mixed evidence on the impact on falls and injuries. Ambrose et al. (2018) identified that energy efficiency interventions can increase the indoor temperature, which, the authors argued, is of particular benefit to elderly individuals because it reduces the risk of falls and fractures. The authors do not provide information on why this might be. No p-value is provided. However, Rodgers et al. (2018) found no statistically significant difference between the intervention group (whose houses received wall and loft insulation) and the control group in terms of emergency hospital admissions for injuries (Rodgers et al., 2018).

Finally, one study explored the impact on headaches after the introduction of fabric works. Although the trend was an improvement in the recovery of headaches, this was not found to be statistically significant.[129] In addition, no significant difference was found between fabric works and the onset of headaches (Curl & Kearns, 2015).

[126] $p=1.000$.
[127] $p=0.100$.
[128] $p=0.016$.
[129] $p=>0.05$, OR 1.47, 95% CI 0.36 to 5.97.

Discussion and conclusions

This chapter provides a summary of the results and their implications. It also highlights gaps in the evidence.

Summary of the findings

The prevalence of poor indoor heating, which includes such factors as old or faulty heating systems, insufficient ventilation or insulation and the use of coal or biomass for fuel, is relatively high in the UK. These conditions are often associated with fuel poverty, which in turn is linked to low income on the one hand and higher than average heating costs, i.e. inefficient heating, on the other. Other groups associated with a greater risk of living in a home with poor heating include children, elderly people and with people with existing health conditions.

The optimal indoor temperature for healthy individuals is between 18°C and 21°C. However, the evidence behind these recommendations is not always clear and may need updating to include guidance for individuals who are not healthy or may be more at risk of developing the health conditions associated with living in a cold home.

The health impacts of poor indoor heating vary depending on the health outcome of focus, although the evidence generally indicates a worsening of health as a result of living in a home with poor heating. Cold-related mortality and morbidity, blood pressure, mental health and strength and dexterity were all found to be linked to living in cold homes. Mixed evidence was found for respiratory outcomes. None of the evidence the research team reviewed reports positive health outcomes as a result of living in a home with poor heating. The studies the research team reviewed do not often provide details on the causal link between poor indoor heating and these health outcomes, making it difficult to understand why these effects occur. Many of the reviewed studies hypothesised that low temperatures may contribute to the development of damp and mould. This was thought to increase the risk of poor health outcomes, particularly respiratory and cardiovascular conditions.

The number of studies the research team reviewed investigating the wider societal impacts of poor heating was limited. The findings suggest a negative impact on school and work attendance, performance and productivity, as well as air pollution and economic outcomes (both at an individual and at a healthcare system level). The contribution to air pollution from poor domestic heating is of particular concern in light of increasing climate change and may reflect that more work is needed to improve or replace these systems with more efficient systems. However, the research team did not specifically explore the environmental effects of energy efficiency systems as a part of this research. The finding by the studies the study team reviewed that there are increased financial costs to the healthcare system from the health impacts of living in homes with poor heating is particularly important, as it shows that poor heating is adding to the financial costs of an already burdened NHS.

The evidence suggests energy efficiency improvements (such as improved ventilation and insulation, energy retrofit and renewable heating technologies) can improve some aspects of the indoor environment, including temperature, humidity, dampness and some air pollutants. The improvement in indoor temperature is of particular importance as it may help to mitigate the negative health outcomes identified in this review that are associated with living in a cold home. However, an increase in radon and mould were seen with some interventions. It may be that individual measures have different impacts depending on the type of environmental factor they are intended to address and whether they are used in combination with other measures. However, the research team found it was difficult to distinguish these differences as many of the studies explored the impacts of multiple energy efficiency improvements together and did not provide the outcomes of individual improvements. It is also important that the systems are functioning properly, as faulty systems can worsen the indoor environment.

The health impacts of energy efficiency systems generally suggest either improvements in health outcomes or no influence on the risk of developing health conditions, which can be taken as a positive outcome. The evidence reviewed suggests that improvements may be particularly beneficial for those with cardiovascular conditions and may help to improve well-being, respiratory conditions and general physical health. Although the reason for this improvement was often not explored in the reviewed literature, authors often hypothesised that an increase in indoor temperatures reduced damp and mould, which may contribute to improvements in respiratory and cardiovascular conditions. In addition, energy efficient heating interventions can contribute to lower energy bills and increased thermal comfort, which the authors hypothesised improved mental health outcomes and well-being. Some evidence reviewed was fairly mixed, suggesting both improvements to health and no association between health and energy efficiency measures. This may be because energy efficiency methods improve some aspects of health but not others and so measuring overall general health does not identify this specific detail. In addition, as discussed in other sections, many of the papers reviewed exploring the impact of energy efficiency systems looked at the effects of multiple energy efficiency measures together, rather than individual systems that may have different effects on health outcomes from each other.

This study highlights gaps in the evidence that future research should fill to understand the whole picture of the effects of poor and energy efficient heating

This rapid evidence assessment has brought together the evidence base for the impact of different heating systems on health and wider factors. The research team has identified gaps in this evidence that could be filled in to get a better overall and in-depth understanding of the impacts of heating systems. However, it is important to note that because of the fairly restrictive literature search used (i.e. all literature review studies from the past ten years and all UK non-review studies from the past five years), the research team cannot say for certain that the gaps in the evidence are due a lack of research, rather than the search restrictions.

The research aims focused on the impact of poor indoor heating that resulted in cold homes, but also on indoor temperatures that are too high. Although there was some evidence on the effects of homes that are too warm, this was very limited and did not provide much information as to the statistical significance of the relationship between heating systems (both poor systems and energy efficient ones) and health and other outcomes. Although understanding the impacts of high temperatures has been less of a priority in the UK because of the mild climate, this is becoming more important as temperatures start to rise as a result of climate change. As has been highlighted throughout this report, much of the literature reviewed investigated the impacts of cold homes (without specifying what types of heating systems they were focused on) or on multiple energy efficiency improvements together (rather than exploring the impacts of one type of system). On the one hand, this is helpful in getting a real-world view of the types of impacts these systems may have, as it is likely that homes have multiple systems together. This is particularly evident from the papers reviewed, in which energy efficiency programmes tended to provide homes with a variety of new heating systems. On the other hand, this may have contributed to the mixed evidence base as to the impacts of heating systems, particularly on health outcomes, as it is possible that different systems result in different health outcomes. Therefore it may be useful for future research to first explore the impacts of individual types of heating system and to then explore the impacts of these together to compare the outcomes.

Although the research team identified a relatively large amount of literature relating to the health impacts of heating systems, particularly poor heating, the literature on other impacts (wider society for poor heating and indoor environment for energy efficient heating) was much more limited. It is important to understand the wider societal impacts of poor indoor heating as these extend beyond the individual and can impact those not living in homes with poor heating, for example, by contributing to increasing air pollution levels.

In addition, it appears that energy efficiency improvements have varying impacts on the indoor environment depending on the type of factor and the type of heating system. It is important to understand these differences to ensure there are no unintended negative consequences from introducing energy efficiency systems, including when they are combined with other systems. For example, evidence suggests that mechanical ventilation can reduce the amount of outdoor pollution entering inside. But it may lead to higher levels of indoor radon when combined with airtightness, which can contribute to lung cancer development. In addition, certain energy efficiency measures can improve one aspect of the indoor environment but worsen others. For example, insulation was shown to increase the indoor temperature but contribute to mould development. Further research is needed to understand the possible unintended consequences of introducing these improvements. In addition, a small number of studies reviewed highlighted the importance of ensuring these systems are functioning correctly. If they are not, they could have detrimental impacts on the quality of the indoor environment. More research is therefore needed to understand the effect of energy efficiency systems not functioning at 100% (which Milner et al. (2014) suggest is a common problem in the UK).

Although part of the research questions included understanding the impacts of heating systems on individuals in the workplace, the research team found very limited evidence exploring this. It is important to understand the effects of different heating systems both at home and in the workplace, particularly as UK adults spend much of their time at work. It is also important to explore these impacts across a range of different work environments, not just offices (which the studies reviewed focused on). Our research questions also aimed to understand the impacts of heating-related ‘smart’ technologies on health and the indoor environment. However, the research team did not find any high-quality evidence focusing on this type of technology. This is an important gap in the research as smart technologies increase in use across the UK and their use may be particularly applied to those more at risk of developing the health conditions associated with poor heating, such as the elderly and the disabled.

Finally, as discussed earlier in this section, the causal links between various heating systems, energy efficiency measures and their outcomes are often not investigated in the literature, meaning the studies only look at correlations. However, understanding these mechanisms is important to be able to address the causes of any negative effects that arise. This is particularly relevant when looking at health impacts, as there are many confounding factors that can influence illness development and progression, especially poverty, which is strongly linked to living in a home with poor heating.

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