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

Technical report

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Any enquiries regarding this publication should be sent to us at:
heatnetworks@beis.gov.uk

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Methodology and research design

This technical report accompanies the results report for the 2020 heat, energy efficiency, smart technology and health evidence review. This evidence review was commissioned in 2019 by the Department for Business, Energy & Industrial Strategy (BEIS) to explore the health and wider societal impacts of poor indoor heating in the home and the workplace. The review also aimed to explore the impacts on human health and the indoor environment of introducing energy efficient and smart heating systems.[1]

To identify evidence of the impact of poor indoor heating on human 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.[2] Rapid evidence assessments are particularly useful for researching a topic area in which the evidence base is unclear, as is the case with this subject area.

Rapid evidence assessments systematically follow seven stages[3]:

1. Scope the review and define research questions;
2. Establish inclusion/exclusion criteria;
3. Carry out the literature search;
4. Screen the results against the inclusion/exclusion criteria;
5. Critically appraise the included studies;
6. Analyse the results; and
7. Write up the results.

The approach the research team took for each of these stages as part of this study will be discussed throughout this chapter.

[1] Hocking, L; Gkousis, E; Smith, P & Gehrt, D. Heat, energy efficiency, smart technology and health: A review of evidence from high-income countries, with a focus on the UK. Results report. BEIS Research Paper 2020/022. London: BEIS.

[2] Center for Evidence-based Management. (2019). What is a rapid evidence assessment (REA)? As of 21 October 2019: https://www.cebma.org/faq/what-is-an-rea/

[3] This is based on the approach for systematic reviews outlined in Petticrew, M., & Roberts, H. (2006). *Systematic reviews in the social sciences: A practical guide*. Wiley. https://onlinelibrary.wiley.com/doi/book/10.1002/9780470754887

Scoping the review and defining the research questions

The study team and BEIS jointly developed four overarching research questions and related sub-research questions, as outlined in Table 1. The sub-research questions helped to guide the rapid evidence assessment and support the development of a precise search strategy. If articles covered the overarching questions but not the sub-research questions, they were still included for full-text extraction.

Table 1: Research and sub-research questions

Overarching question	Sub-questions
1.What is the impact of poor indoor heating on health?	a. What are the impacts of homes and workplaces with poor heating (as well as of its consequences such as mould and damp) on adults' and children's physical and mental health, including perceptions of health?
	b. Which populations are most affected by conditions related to poor indoor heating?
	c. What are the morbidity/mortality rates associated with having homes that are too hot or too cold, draughty, damp and/or with poor gas stoves/boilers?
	d. Is there an optimal temperature for sleeping?
	e. What proportion of a person's air pollution exposure (as well as consequential health issues) is due to heating systems and gas cookers/hobs?
	f. How do heating consumption and associated behaviours vary depending on people's health conditions?
	g. What are the indoor air pollution-related health impacts of oil boilers, gas boilers, heat pumps, biomass boilers and coal back boilers?
2. What are the wider societal impacts of poor indoor heating?	a. What are the economic costs of health conditions related to poor indoor heating?
	b. What are the impacts of homes that are too hot, too cold and/or damp on children's academic attainment?
	c. How does the temperature of workplaces affect productivity?
3. What is the impact of energy efficiency improvements, renewable heating technologies and smart technology on the indoor environment?	a. What are the impacts of energy efficiency improvements (including combinations of interventions) on indoor air quality in homes and workplaces? (What are the implications for permeability, room temperature, damp, mould and water vapour levels?)
	b. How do different low carbon heating technologies impact on the indoor air quality of a property?

Overarching question	Sub-questions
4. What is the impact of energy efficiency improvements, renewable heating technologies and smart technology on health?	a. What are the impacts of installing specific energy efficiency measures (e.g. solid wall insulation, draught-proofing and mechanical ventilation with heat recovery) on health? b. What are the impacts of moving to low carbon heating (e.g. heat pumps, fuel cells, hydrogen boilers, heat networks) have on people's health?

The research team has interpreted the term 'indoor heating' to span a broad range of systems. These have largely been split into those considered 'poor', to cover research questions 1 and 2, and those considered energy efficient and renewable, to cover research questions 3 and 4. This includes, but is not restricted to, the following examples:

- Poor heating:
    - Lack of or faulty central heating;
    - Use of boiler or other heating systems considered to be of poor quality, i.e. back boilers, non-condensing boilers (the definitions of these are discussed in more detail in the results report);
    - Use of coal or biomass for heating;
    - Use of gas for cooking or heating, e.g. gas cookers and boilers (which may lead to increased levels of indoor pollution); and
    - Lack of or poor ventilation (which may contribute to excess indoor temperature or pollution) and insulation.
- Measures to improve the energy efficiency of buildings:
    - Insulation;
    - Ventilation (including extractor systems and mechanical ventilation, which can contribute to improved indoor temperatures and air quality);
    - Heat recovery[4]; and
    - Energy retrofit (which often includes multiple types of energy efficient heating approaches).
- Heating technologies based on renewable energy sources (such as solar panels and heat pumps).
- Smart technologies to better control heating systems.

The research team also included articles that covered multiple types of the above approaches. And it included articles that did not define a particular type of heating but referred to, for example, cold homes or fuel poverty in general.

[4] A heat recovery system works independently of the main heating system in a building. It removes the heat from 'stale' air and recirculates it around the building. At the same time, it allows the stale air to be expelled outdoors.

Establishing exclusion and inclusion criteria

Exclusion and inclusion criteria are used to determine which articles should be included for full-text analysis. They are used both to help develop the search (and to restrict the search to ensure the records identified are relevant and manageable in number) and to screen titles and abstracts identified through the search to determine whether they should be included.

The research team developed the exclusion and inclusion criteria for this rapid evidence assessment 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. The criteria used and the reasoning behind their use are presented in Table 2.

Table 2: Exclusion and inclusion criteria applied during the literature search and during the screening of abstracts and titles

Metadata	Inclusion criteria	Exclusion criteria	Reason
Inclusion and exclusion criteria applied during the literature search			
Publication date	2010 or later	Pre-2010	A medium-range time period of nine years, suggested by BEIS based on their knowledge of the available literature, allows us to identify as much of the relevant literature as possible while ensuring the evidence is still up to date.
Location[5]	High-income countries (countries in Europe, USA, Canada, Japan, South Korea, Australia, New Zealand)	Low- or middle-income countries	Evidence from low- and middle-income countries is less likely to be relevant for a UK context.
Language	English	Non-English-language	Searching only English papers is likely to cover the majority of relevant literature
Publication type	Peer-reviewed journal publications, PhD theses, documents with clear authorship, books	Autobiography; Bibliography; Biography; Clinical Trial Protocol; Clinical Trial, Comment; Dictionary; Directory; Duplicate Publication; Editorial; Electronic Supplementary Materials; Festschrift; Historical Article; Interactive Tutorial; Introductory Journal Article; Lecture; Legal Case; Letter; News; Newspaper Article; Observational Study, Veterinary;	Evidence from these publication types increases the likelihood of covering a high-quality evidence base and removes some irrelevant studies.

[5] Some studies from low- and middle-income countries were still picked up during the final search. These were excluded at the screening stage.

Metadata	Inclusion criteria	Exclusion criteria	Reason
Topic	Non-smoking	Smoking	Testing of the PubMed search strategy identified a very large number of hits, many of which were related to smoking, which is outside the scope of this research. To reduce the number of hits to a more manageable number, various terms related to smoking were used to exclude these articles (see Annex A for more detail).
Inclusion and exclusion criteria applied during the screening of abstracts and titles			
Study participants	Humans	Animals	This research is focusing on the human health impacts of indoor heating only.
Study location	Homes and workplaces	Schools or other child education or care facilities	This research is focusing on the impact of poor indoor heating in homes and workplaces only.
Topic	Explicit linking of health or other impacts to at least one aspect of indoor heating	Health or other impacts without linking this to indoor heating	If impacts are not linked to indoor heating, it cannot be concluded that the impacts occurred as a result of the heating system.
	The subsequent health and wider societal impacts of indoor heating	Indoor heating without reference to health and wider societal impacts	This research is focusing on the health and wider societal impacts that occur as a result of poor indoor heating and energy efficient heating.
	Poor indoor heating not the result of a natural disaster	Poor indoor heating as a result of a natural disaster	Natural disasters, such as hurricanes, are not relevant to a UK context. The research also focused on the health impacts of indoor heating on a day-to-day basis, rather than after a serious incident.

Metadata	Inclusion criteria	Exclusion criteria	Reason
	Pollution resulting from indoor cooking systems	Pollution resulting from outdoor cooking systems, such as barbeques	Part of this research is focusing on the impact of heating systems, which includes cooking systems, on indoor pollution, rather than outdoor.
	The health and wider social impacts of indoor pollution	The health and wider societal impacts of outdoor pollution	This research is focusing on the health impacts as a result of indoor pollution from heating systems only.
	The health and wider social impacts of high/low indoor temperature exposure	The health and wider social impacts of high/low outdoor temperature exposure	This research is focusing on the health impacts as a result of indoor temperature.

Screening against the inclusion and exclusion criteria

The research team screened the titles and abstracts of the search results against the additional inclusion and exclusion criteria outlined in Table 2 to decide which papers should be taken forward for full-text analysis. The research team conducted an initial screening of all sets of literature on their relevance to the research questions and country coverage. Researchers selected papers with information relevant to at least one of the research questions and that were conducted in high-income countries for inclusion. For these papers identified as relevant based on their title and abstract, researchers recorded the research question(s) each paper related to. To ensure reliability and consistency throughout the screening process, two researchers double-screened 20 of the grey literature documents identified from the NICE Evidence Library (as this was the first database to be searched). In addition, the research team discussed and decided any queries of uncertainties about papers among themselves. These discussions primarily occurred on an ad-hoc basis during the early phases of the screening.

This stage resulted in 645 articles that the team considered to be relevant to the research questions and that were taken forward to the quality assessment stage. This number of papers (645) is very high, and the research team were unable to assess the quality of each of these individually due to resource constraints. 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.[6]

This led to 143 papers being taken forward for quality assessment. A summary of the numbers of papers identified up to this point can be found in Figure 1.

Carrying out the literature search

This rapid evidence assessment involved searching three different literature sources. 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 NICE Evidence

[6] 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.

library covers published literature on health, social care and public health, and the EU Energy Poverty Observatory is a knowledge hub bringing together reports related to energy poverty from across the EU. BEIS also provided a set of literature identified before the start of the study, which consisted of both academic and grey literature.

The search terms for PubMed were developed in consultation with BEIS. The search string for this can be found in Annex A. This search returned **10,643** papers of potential relevance to be screened against the inclusion and exclusion criteria set out in Table 2. These were split between three researchers.

The approach to searching the NICE Evidence Library and the EU Energy Observatory was different from the approach to searching PubMed, because long and complex search strings cannot be used. Therefore, the research team adapted the search terms used for PubMed to each of these sources and filtered by articles published since 2010. For the NICE Evidence Library search, the research team used keywords from the PubMed search to identify relevant literature. To identify as many relevant documents as possible, the research team used a total of 62 different keyword combinations. Researchers only extracted search hits for screening if the first page of the search (sorted by relevance, with each page presenting 10 search hits) 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. This resulted in 15 of the 62 search results being screened. Duplicates were removed from the final list of papers. A summary of the search terms used can be found in Annex B. This search returned **1,547** documents to be screened for relevance against the inclusion and exclusion criteria, and these were split between two researchers.

The EU Energy Poverty Observatory is a fairly new initiative. Therefore the research team only searched the term ‘health’, for publications since 2010. The research team also did not restrict the search by country. This resulted in 45 hits, 2 of which were duplicates and were removed. This left **43** articles for screening, which was conducted by one member of the research team.

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. Duplicates with the other three literature sources were removed, which resulted in **56** of these resources being screened, by one member of the research team.

Critically appraising the included studies

Before conducting a full-text analysis of the relevant articles identified through the screening process, the research team assessed the quality of the articles to ensure the results and conclusions were based on high-quality evidence conform the criteria in Table 3. The team developed the academic criteria based on criteria previously used by RAND Europe.[7] It adapted the grey literature criteria from the Authority, Accuracy, Coverage, Objectivity, Date,

[7] Guthrie, S., Lichten, C., van Belle, J., Ball, S., Knack, A., & Hofman, J. (2017). Understanding mental health in the research environment: A rapid evidence assessment. Santa Monica, CA: Rand Corporation. As of 21 October 2019: https://www.rand.org/pubs/research_reports/RR2022.html.

Significance (AACODS) checklist, which is recommended for assessing the quality of grey literature.[8]

Table 3: Quality assessment criteria

Academic literature quality assessment criteria	Grey literature quality assessment criteria
Does the study have clear research questions/aims?	Is the organisation/author reputable?
Is the study well designed to reach the research questions/aims?	Is there a clear aim/brief?
Is the sampling approach appropriate and well justified?	Are limitations clearly stated?
Is the data collection approach appropriate and well justified?	Does the document seem to be objective and balanced?
Are the data appropriately analysed and the findings adequately corroborated?	Does the document have a clear publication date?
Does the interpretation of the findings adequately reflect the assumptions made, limitations of the method, and any issues around generalisability of the findings?	Is the document significant? I.e. is it meaningful and does it add context or enrich the research area?
Each assessment criterion marked as: • Addressed the criteria clearly and fully • Addressed the criteria partially • Did not address the criteria	Each assessment criterion marked as: • Yes • No
Those with any criteria marked as 'did not address the criteria' were excluded	Those with any criteria marked as 'no' were excluded

Of the 143 articles that were quality assessed, 59 were excluded because they did not meet one or more of the quality assessment criteria, leaving 84 of high quality. However, when the research team explored the distribution of articles covering each research question, it became clear these 84 articles included 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. They, therefore, in consultation with BEIS, made the decision to include articles from the past 5 years from countries other than the UK that related to research question 2. These articles were quality assessed against the criteria in Table 3.

[8] Tyndall, J. 2010. Authority, Accuracy, Coverage, Objectivity, Date, Significance (AACODS) checklist. https://dspace.flinders.edu.au/xmlui/bitstream/handle/2328/3326/AACODS_Checklist.pdf;jsessionid=7BA5880649DC126EB10C972024D98B1B?sequence=4

Seven articles were deemed to be of high quality and taken forward for full-text extraction. Only information relevant to research question 2 was extracted from these studies.

Therefore, **91** articles were deemed to be of high quality and were taken forward for full-text extraction. A summary of these numbers and how they were reached can be found in Figure 1.

Analysing the results

The research team created an Excel extraction template to identify relevant information from the literature. This included[9]:

- Information on the study population, such as age or socioeconomic status.
- The heating or ventilation system of focus, such as central heating or mechanical ventilation.
- Information on the prevalence of poor indoor heating.
- Information on populations more at risk of living in homes with poor heating.
- Information related to research question 1: What is the impact of poor indoor heating on health?
    - The health condition, e.g. asthma, blood pressure;
    - The type of impact (positive, neutral, negative);
    - Populations more at risk of the health impacts; and
    - Details on the health impact, including significance values where provided, e.g. p-value.
- Information related to research question 2: What are the wider societal impacts of poor indoor heating?
    - Type of impact, e.g. attendance, healthcare costs;
    - The type of impact (positive, neutral, negative);
    - Populations more at risk for the societal impacts; and
    - Details on the societal impact, including significance values where provided, e.g. p-value.
- Information related to question 3: What is the impact of energy efficiency improvements, renewable heating technologies and smart technology on the indoor environment?
    - Type of impact, e.g. change in indoor temperature, change in humidity level;
    - The type of impact (positive, neutral, negative);
    - Populations most likely to be affected; and
    - Details on the impact, including significance values where provided, e.g. p-value.

[9] Not all articles contained information relevant to each of these points.

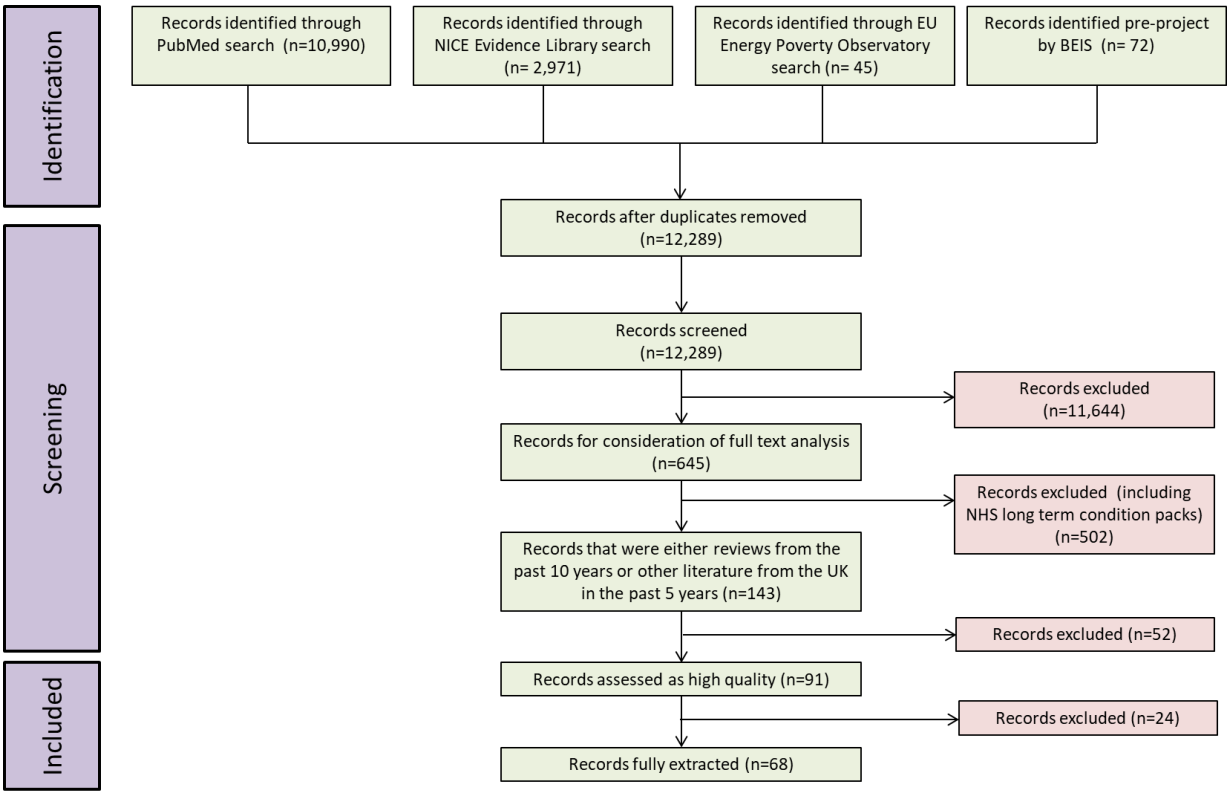
- Information related to question 4: What is the impact of energy efficiency improvements, renewable heating technologies and smart technology on health?
    - The health condition, e.g. asthma, blood pressure;
    - The type of impact (positive, neutral, negative);
    - Populations most likely to be affected; and
    - Details on the health impact, including significance values where provided, e.g. p-value.
- Information on study limitations.
- Additional comments and notes from research team.

Full-text extraction was conducted by three researchers.

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, for example, non-review articles that did not focus on the UK or articles that did not explicitly link measured outcomes to heating. In addition, there were some duplicates remaining in the set of literature, primarily articles that were found to be chapters of larger reports. A further 25 papers were excluded on this basis. This left **68** articles that were extracted.

The PRISMA diagram below shows the full process of searching, screening and quality assessing the literature and how the 68 articles for full-text analysis were selected (Figure 1).

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



Source: Adapted from Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G., The PRISMA Group (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. PLoS Med, 6(7), e1000097. https://doi.org/10.1371/journal.pmed.1000097.

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[10] and other statistical significance information, including confidence interval (CI),[11] odd ratio (OR),[12] incidence rate ratio (IRR)[13] and relative odds ratio (ROR),[14] 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.

[10] 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.
[11] 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.
[12] Odds ratios statistically quantify the association between two interventions.
[13] A rate ratio is used to compare the incidence rates of events at certain points in time.
[14] 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.

Annex A: PubMed search strings

Search 1: Impact of poor indoor heating on health

"poor heat"[tiab] OR "poor heating"[tiab] OR "poor energy"[tiab] OR indoor heat*[tiab] OR (house[tiab] AND heat[tiab]) OR (house[tiab] AND heating[tiab]) OR (housing[tiab] AND heat[tiab]) OR (home[tiab] AND heat[tiab]) OR (home[tiab] AND heating[tiab]) OR (homes[tiab] AND heat[tiab]) OR (working[tiab] AND heat[tiab]) OR (working[tiab] AND heating[tiab]) OR occupational heat*[tiab] OR (workplace*[tiab] AND heat*[tiab]) OR “low energy efficiency”[tiab] OR (draught*[tiab] AND (indoor*[tiab] OR house*[tiab] OR building*[tiab])) OR (draft*[tiab] AND (indoor*[tiab] OR house*[tiab] OR building*[tiab]))OR (moisture[tiab] AND (indoor*[tiab] OR house*[tiab] OR building*[tiab])) OR ((humid[tiab] OR humidity[tiab]) AND (indoor*[tiab] OR house*[tiab] OR building*[tiab])) OR indoor air pollution*[tiab] OR indoor pollution*[tiab] OR indoor pollutant*[tiab] OR indoor air qualit*[tiab] OR fans[tiab] OR venting[tiab] OR ((home[tiab] AND ventilation[tiab]) OR (basement[tiab] AND ventilation[tiab]) OR “indoor temperature”[tiab] OR “indoor temperatures”[tiab] OR (indoor[tiab] AND permeability[tiab]) OR ("indoor"[tiab] AND "water vapour"[tiab]) OR ("indoor"[tiab] AND "water vapor"[tiab]) OR insulation[tiab] OR “carbon monoxide”[tiab] OR boiler[tiab] OR boilers[tiab] OR central heat*[tiab] OR gas stove*[tiab] OR ((heat[tiab] OR heater[tiab] OR heaters[tiab] OR heating[tiab]) AND fuel[tiab])) OR heat pump*[tiab] OR heat use[tiab] OR heating use[tiab] OR heater use[tiab] OR ((heat[tiab] OR heater[tiab] OR heaters[tiab] OR heating[tiab]) AND usage[tiab])) OR ((heat[tiab] OR heater[tiab] OR heaters[tiab] OR heating[tiab]) AND consumption[tiab])) OR indoor overheat*[tiab] OR excess heat[tiab] OR excess cold[tiab] OR cold home*[tiab] OR fuel poverty[tiab] OR radon[tiab] OR solid fuel*[tiab] OR thermal discomfort[tiab] OR pollutant exposure[tiab] OR pollutants exposure[tiab] OR (condensation[tiab] AND (window*[tiab] OR indoor*[tiab] OR interior*[tiab])) OR ((indoor*[tiab] OR building[tiab] OR hous*[tiab]) AND (mold*[tiab] OR mould*[tiab])) OR (damp*[tiab] AND (building*[tiab] OR indoor*[tiab] OR house*[tiab] OR home[tiab])) OR ((radiation[tiab] AND (building* OR house*[tiab] OR indoor*[tiab])) NOT “radiation therapy”[tiab])

AND
health impact*[tiab] OR sick[tiab] OR sickness[tiab] OR unwell[tiab] OR ill[tiab] OR illness[tiab] OR wellbeing[tiab] OR breath*[tiab] OR respiratory disease*[tiab] OR respiratory infection*[tiab] OR infectious disease*[tiab] OR asthma[tiab] OR asthmatic[tiab] OR asthmatics[tiab] OR fatigue[tiab] OR malaise[tiab] OR tiredness[tiab] OR chronic disease*[tiab] OR morbidity[tiab] OR death*[tiab] OR mortal[tiab] OR mortals[tiab] OR mortality[tiab] OR cancer[tiab] OR "carbon monoxide poisoning"[tiab] OR “co poisoning”[tiab] OR physical health[tiab] OR mental health[tiab] OR wheeze[tiab] OR wheezes[tiab] OR wheezed[tiab] OR

wheezing[tiab] OR eczema[tiab] OR cough[tiab] OR dermatitis[tiab] OR pneumonia[tiab] OR “heat edema”[tiab] OR heat rash*[tiab] OR heat cramp*[tiab] OR heat exhaustion[tiab] OR heat syncope[tiab] OR emotional stress*[tiab] OR anxiety[tiab] OR anxieties[tiab] OR sleep disturbance[tiab] OR sleep disorder*[tiab] OR sleeping disorder[tiab] OR "excess winter deaths"[tiab] OR EWD[tiab] OR depression[tiab] OR cardiovascular disease*[tiab] OR cardiovascular infection*[tiab] OR high blood pressure[tiab] OR heart attack*[tiab] OR stroke[tiab]

AND

(humans[mh] OR inprocess[sb] OR publisher[sb] OR pubmednotmedline [sb])

Search 2: Impact of poor indoor heating on wider society

"poor heat"[tiab] OR "poor heating"[tiab] OR "poor energy"[tiab] OR indoor heat*[tiab] OR (house[tiab] AND heat[tiab]) OR (house[tiab] AND heating[tiab]) OR (housing[tiab] AND heat[tiab]) OR (home[tiab] AND heat[tiab]) OR (home[tiab] AND heating[tiab]) OR (homes[tiab] AND heat[tiab]) OR (working[tiab] AND heat[tiab]) OR (working[tiab] AND heating[tiab]) OR occupational heat*[tiab] OR (workplace*[tiab] AND heat*[tiab]) OR “low energy efficiency”[tiab] OR (draught*[tiab] AND (indoor*[tiab] OR house*[tiab] OR building*[tiab])) OR (draft*[tiab] AND (indoor*[tiab] OR house*[tiab] OR building*[tiab]))OR (moisture[tiab] AND (indoor*[tiab] OR house*[tiab] OR building*[tiab])) OR ((humid[tiab] OR humidity[tiab]) AND (indoor*[tiab] OR house*[tiab] OR building*[tiab])) OR indoor air pollution*[tiab] OR indoor pollution*[tiab] OR indoor pollutant*[tiab] OR indoor air qualit*[tiab] OR fans[tiab] OR venting[tiab] OR ((home[tiab] AND ventilation[tiab]) OR (basement[tiab] AND ventilation[tiab]) OR “indoor temperature”[tiab] OR “indoor temperatures”[tiab] OR (indoor[tiab] AND permeability[tiab]) OR ("indoor"[tiab] AND "water vapour"[tiab]) OR ("indoor"[tiab] AND "water vapor"[tiab]) OR insulation[tiab] OR “carbon monoxide”[tiab] OR boiler[tiab] OR boilers[tiab] OR central heat*[tiab] OR gas stove*[tiab] OR ((heat[tiab] OR heater[tiab] OR heaters[tiab] OR heating[tiab]) AND fuel[tiab])) OR heat pump*[tiab] OR heat use[tiab] OR heating use[tiab] OR heater use[tiab] OR ((heat[tiab] OR heater[tiab] OR heaters[tiab] OR heating[tiab]) AND usage[tiab])) OR ((heat[tiab] OR heater[tiab] OR heaters[tiab] OR heating[tiab]) AND consumption[tiab])) OR indoor overheat*[tiab] OR excess heat[tiab] OR excess cold[tiab] OR cold home*[tiab] OR fuel poverty[tiab] OR radon[tiab] OR solid fuel*[tiab] OR thermal discomfort[tiab] OR pollutant exposure[tiab] OR pollutants exposure[tiab] OR (condensation[tiab] AND (window*[tiab] OR indoor*[tiab] OR interior*[tiab])) OR ((indoor*[tiab] OR building[tiab] OR hous*[tiab]) AND (mold*[tiab] OR mould*[tiab])) OR (damp*[tiab] AND (building*[tiab] OR indoor*[tiab] OR house*[tiab] OR home[tiab])) OR ((radiation[tiab] AND (building* OR house*[tiab] OR indoor*[tiab])) NOT “radiation therapy”[tiab])

AND

educational achievement[tiab] OR educational attainment[tiab] OR school performance[tiab] OR academic achievement[tiab] OR work productivity[tiab] OR labour productivity[tiab] OR labor productivity[tiab] OR income[tiab] OR earnings[tiab] OR wage[tiab] OR (school[tiab] AND days[tiab] AND lost[tiab]) OR (school[tiab] AND missed[tiab]) OR missed school[tiab] OR workdays lost[tiab] OR lost workdays[tiab] OR (work[tiab] AND missed[tiab]) OR missed work[tiab] OR health cost*[tiab] OR healthcare cost*[tiab] OR economic cost*[tiab] OR employment[tiab] OR "means tested benefit"[tiab] OR welfare[tiab] OR health saving*[tiab] OR (healthcare[tiab] AND saving[tiab]) OR QUALYS[tiab] OR "quality adjusted life years"[tiab] OR independent living[tiab]

AND
(humans[mh] OR inprocess[sb] OR publisher[sb] OR pubmednotmedline [sb])

Search 3: Impact of energy efficient improvements on indoor air quality and health

renewable technolog*[tiab] OR (insulation[tiab] AND (home[tiab] OR house*[tiab] OR building*[tiab])) OR “draft proof”[tiab] OR “draught proof”[tiab] OR (“mechanical ventilation”[tiab] AND “heat recovery”[tiab]) OR “heat pump”[tiab] OR fuel cell*[tiab] OR (hydrogen[tiab] AND boiler*[tiab]) OR “heat network”[tiab] OR “heat networks”[tiab] OR (heat*[tiab] AND panel*[tiab]) OR air condition*[tiab] OR retrofit[tiab] OR “smart energy meter”[tiab] OR “smart meter”[tiab] OR “time of use”[tiab] OR “demand shift”[tiab] OR “smart appliance”[tiab] OR (electric*[tiab] AND storage*[tiab]) OR battery[tiab] OR batteries[tiab] OR “electric vehicle charge”[tiab] OR vcharge[tiab] OR “building upgrade”[tiab] OR “building upgrades”[tiab] OR “warm building”[tiab] OR “warm buildings”[tiab] OR thermal quality[tiab] OR low carbon technology[tiab] OR smart control[tiab] OR ((storage[tiab] OR flexible[tiab]) AND tariff[tiab])

AND

"poor heat"[tiab] OR "poor heating"[tiab] OR "poor energy"[tiab] OR indoor heat*[tiab] OR (house[tiab] AND heat[tiab]) OR (house[tiab] AND heating[tiab]) OR (housing[tiab] AND heat[tiab]) OR (home[tiab] AND heat[tiab]) OR (home[tiab] AND heating[tiab]) OR (homes[tiab] AND heat[tiab]) OR (working[tiab] AND heat[tiab]) OR (working[tiab] AND heating[tiab]) OR occupational heat*[tiab] OR (workplace*[tiab] AND heat*[tiab]) OR “low energy efficiency”[tiab] OR (draught*[tiab] AND (indoor*[tiab] OR house*[tiab] OR building*[tiab])) OR (draft*[tiab] AND (indoor*[tiab] OR house*[tiab] OR building*[tiab]))OR (moisture[tiab] AND (indoor*[tiab] OR house*[tiab] OR building*[tiab])) OR ((humid[tiab] OR humidity[tiab]) AND

(indoor*[tiab] OR house*[tiab] OR building*[tiab])) OR indoor air pollution*[tiab] OR indoor pollution*[tiab] OR indoor pollutant*[tiab] OR indoor air qualit*[tiab] OR fans[tiab] OR venting[tiab] OR ((home[tiab] AND ventilation[tiab]) OR (basement[tiab] AND ventilation[tiab]) OR “indoor temperature”[tiab] OR “indoor temperatures”[tiab] OR (indoor[tiab] AND permeability[tiab]) OR ("indoor"[tiab] AND "water vapour"[tiab]) OR ("indoor"[tiab] AND "water vapor"[tiab]) OR insulation[tiab] OR “carbon monoxide”[tiab] OR boiler[tiab] OR boilers[tiab] OR central heat*[tiab] OR gas stove*[tiab] OR ((heat[tiab] OR heater[tiab] OR heaters[tiab] OR heating[tiab]) AND fuel[tiab])) OR heat pump*[tiab] OR heat use[tiab] OR heating use[tiab] OR heater use[tiab] OR ((heat[tiab] OR heater[tiab] OR heaters[tiab] OR heating[tiab]) AND usage[tiab])) OR ((heat[tiab] OR heater[tiab] OR heaters[tiab] OR heating[tiab]) AND consumption[tiab])) OR indoor overheat*[tiab] OR excess heat[tiab] OR excess cold[tiab] OR cold home*[tiab] OR fuel poverty[tiab] OR radon[tiab] OR solid fuel*[tiab] OR thermal discomfort[tiab] OR pollutant exposure[tiab] OR pollutants exposure[tiab] OR (condensation[tiab] AND (window*[tiab] OR indoor*[tiab] OR interior*[tiab])) OR ((indoor*[tiab] OR building[tiab] OR hous*[tiab]) AND (mold*[tiab] OR mould*[tiab])) OR (damp*[tiab] AND (building*[tiab] OR indoor*[tiab] OR house*[tiab] OR home[tiab])) OR ((radiation[tiab] AND (building* OR house*[tiab] OR indoor*[tiab])) NOT “radiation therapy”[tiab])

OR

health impact*[tiab] OR sick[tiab] OR sickness[tiab] OR unwell[tiab] OR ill[tiab] OR illness[tiab] OR wellbeing[tiab] OR breath*[tiab] OR respiratory disease*[tiab] OR respiratory infection*[tiab] OR infectious disease*[tiab] OR asthma[tiab] OR asthmatic[tiab] OR asthmatics[tiab] OR fatigue[tiab] OR malaise[tiab] OR tiredness[tiab] OR chronic disease*[tiab] OR morbidity[tiab] OR death*[tiab] OR mortal[tiab] OR mortals[tiab] OR mortality[tiab] OR cancer[tiab] OR "carbon monoxide poisoning"[tiab] OR “co poisoning”[tiab] OR physical health[tiab] OR mental health[tiab] OR wheeze[tiab] OR wheezes[tiab] OR wheezed[tiab] OR wheezing[tiab] OR eczema[tiab] OR cough[tiab] OR dermatitis[tiab] OR pneumonia[tiab] OR “heat edema”[tiab] OR heat rash*[tiab] OR heat cramp*[tiab] OR heat exhaustion[tiab] OR heat syncope[tiab] OR emotional stress*[tiab] OR anxiety[tiab] OR anxieties[tiab] OR sleep disturbance[tiab] OR sleep disorder*[tiab] OR sleeping disorder[tiab] OR "excess winter deaths"[tiab] OR EWD[tiab] OR depression[tiab] OR cardiovascular disease*[tiab] OR cardiovascular infection*[tiab] OR high blood pressure[tiab] OR heart attack*[tiab] OR stroke[tiab])

AND
(humans[mh] OR inprocess[sb] OR publisher[sb] OR pubmednotmedline [sb])

Additional restrictions

In addition to the search strings above, each of the three searches had the following exclusion criteria in place for the title and abstract:

- **Country exclusion**: Mozambique[tiab] OR Uganda[tiab] OR Malawi[tiab] OR "South Sudan"[tiab] OR Nepal[tiab] OR Afghanistan[tiab] OR Pakistan[tiab] OR Peru[tiab] OR Bolivia[tiab] OR "South Africa" [tiab] OR Mali[tiab] OR Kenya[tiab] OR Sri Lanka[tiab] OR Haryana[tiab] OR Brazil[tiab] OR Myanmar[tiab] OR Tanzania[tiab] OR Congo[tiab] OR Zambia[tiab] OR Malaysian[tiab] OR Bhilai[tiab] OR Ethiopia[tiab] OR Nigeria[tiab] OR Rwanda[tiab] OR Liberia[tiab] OR Guinea[tiab] OR Sierra Leone[tiab] OR Bangladesh[tiab] OR Zuni[tiab] OR Haiti[tiab] OR China[tiab] OR Senegal[tiab] OR India[tiab] OR Indonesia[tiab] OR Cameroon[tiab] OR Benin[tiab] OR Guatemala[tiab] OR Vietnam[tiab] OR Ghana[tiab] OR Estonia[tiab] OR Taiwan[tiab] OR Taiwanese[tiab] OR Cambodia[tiab] OR Samoa[tiab] OR Thailand[tiab] OR "Sub-Saharan Africa"[tiab] OR Philippines[tiab] OR Zimbabwe[tiab] OR Burkina Faso[tiab] OR "Central America"[tiab] OR Bhutanese[tiab] OR Honduras[tiab] OR Barbados[tiab] OR Saudi Arabia[tiab] OR "Middle East"[tiab] OR Madagascar[tiab] OR Burma[tiab] OR "United Arab Emirates" [tiab] OR Côte d'Ivoire[tiab] OR India[tiab] OR Chile[tiab] OR Iran[tiab] OR Cretan[tiab] OR Nicaragua[tiab] OR Mongolia[tiab] OR Russia[tiab] OR Malaysia[tiab] OR Honduras[tiab] OR Honduran[tiab] OR Egypt[tiab] OR Kazakhstan[tiab] OR Kermanshah[tiab] OR Malawian[tiab] OR Cape Verde[tiab] OR "Republic of Georgia"[tiab] OR Singapore[tiab] OR "South African"[tiab] OR "Chinese cities"[tiab] OR Gaza[tiab]
- **Non-human exclusion**: rat[tiab] OR rats[tiab] OR mouse[tiab] OR mice[tiab] OR horses[tiab] OR cow[tiab] OR cows[tiab] OR monkey[tiab] OR monkeys[tiab] OR rabbit*[tiab]
- **Smoking exclusion**[15]: smoking[tiab] OR smoker[tiab] OR tobacco[tiab] OR cigarette*[tiab]

[15] After running this search, the initial number of hits was very high. It became apparent that many of these papers related to smoking, which is not relevant to this research. To reduce the number of hits to a manageable number, the research team decided to exclude papers with smoking-related terms in the title during the search.

Annex B: NICE Evidence Library search strings

As discussed earlier in this report, the research team screened only those searches in which the first page of results (sorted by relevancy with 10 search hits provided per page) related to at least one of the research questions and contained literature that had not already been identified in a previous keyword search. Table 4 provides an overview of the 62 different searches used in the NICE Evidence Library to identify relevant grey literature that was extracted for screening.

Table 4: Key term searches used for the grey literature search

Search	Number of hits	Results extracted for screening?
home heat technology	590	Yes
"fuel poverty" health	499	Yes
home heating technology	376	Yes
indoor heat* health	368	Yes
"excess winter deaths"	326	Yes
insulation health	254	Yes
insulation home	225	Yes
indoor heat technology	132	Yes
retrofit	65	Yes
"heating system" health	59	Yes
"cold home" health	38	Yes
"cold home" education	22	Yes
"smart meter" health	10	Yes
"heat pump"	7	Yes
"controlled ventilation" heat*	7	Yes
home heat* technology	1664	No
energy efficient home	1277	No
"mechanical ventilation"	1248	No
heat technology	861	No
heat technology health	835	No
heat* workplace	834	No
cold workplace	441	No
home heating technology health	371	No
indoor heat* school	292	No

Search	Number of hits	Results extracted for screening?
"energy efficiency" health	268	No
insulation	262	No
automated ventilation	185	No
renewable heating technology health	159	No
"energy efficient" health	156	No
boiler health	153	No
energy efficient heating	135	No
"mechanical ventilation" heat*	129	No
smart heating health	125	No
hydrogen heat*	110	No
indoor heating technology health	108	No
indoor heat* productivity	102	No
smart heating technology	102	No
smart heating technology health	100	No
"mechanical ventilation" heat* home	88	No
hydrogen heat* home	76	No
automated ventilation heat*	63	No
"controlled ventilation"	56	No
"cold home" cost	35	No
"warm home" health	33	No
"cold home" economic cost	27	No
"heat* system" health	3	No
"low carbon technology" health	3	No
"home heat" health	2	No
"cold work" health	1	No
"thermal quality" health	1	No
"cold home" qualys	0	No
"cold office" health	0	No
"cold workplace"	0	No
"energy efficienc*" health	0	No
"energy efficienc*" health home	0	No
"energy efficienc*" health house	0	No
"heat technology"	0	No
"heat technology" health	0	No
"poor indoor heat" health	0	No

Search	Number of hits	Results extracted for screening?
"smart heating appliance" health	0	No
home "heat technology"	0	No
"automated ventilation"	0	No

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