EVIDENCE REVIEW & ECONOMIC ANALYSIS OF EXCESS WINTER DEATHS

for the National Institute for Health and Care Excellence (NICE)

Economic modelling report

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Executive summary

Aims and objectives

The aim of the project was to model the cost-effectiveness of interventions to reduce the health risks associated with cold homes. The specific objectives were:

- To develop a model of cold-related health impacts based primarily on life table methods.
- To develop a model of the cost-effectiveness of home energy efficiency interventions and fuel subsidies, concentrating on the effects of low temperature but including adverse effects on indoor air quality.
- To assess costs and health and non-health benefits relevant to the interventions.

Methods

A building physics model was developed to quantify changes in indoor environmental conditions (winter indoor temperature, mould and air quality) associated with energy efficiency interventions (improvements to the building fabric and/or altered ventilation control) and to explore the potential impact of additional home heating consequent to fuel subsidy. Health impacts associated with the estimated changes in exposure to occupants were characterised by use of disease-specific life table methods in combination with direct estimates of change in disease prevalence. Costs were assessed in terms of capital investment (largely based on soon to be published data from DECC), changes in energy demand, and costs associated with modelled changes in contacts with the NHS. Incremental cost-effectiveness ratios (ICERs) were computed using a range of input costs and benefits to reflect different accounting perspectives.

Key assumptions

There are multiple assumptions in the economic model. Key assumptions include:

- Changes in indoor temperature are predictable from an empirical relationship between standardized internal temperature (SIT) and the energy efficiency characteristics of the dwelling as reflected by the modelled whole dwelling E-value (W/K).
- For the main intervention scenarios, energy efficiency measures have no impact on ventilation characteristics of the dwelling.
- Health impacts are represented by changes in life expectancy and disease prevalence of a self-replenishing population assumed to experience underlying rates of morbidity and mortality constant at 2010 levels over the 42 years of follow up.
- The targeted populations do not move home at any point following intervention.
- Target groups in relation to dwelling characteristics are adequately represented by sub-samples of the English Housing Survey (EHS) identified from self-reported symptoms, scaled to match national disease prevalence.
- The health effects of changes in indoor temperature can be adequately quantified using a synthesis of evidence from a sparse number of intervention and/or observational studies, and

the impacts of changes in indoor air quality from published epidemiological evidence of varying robustness.

Population

All analyses were based on sub-samples of the population of England identified on the basis of the following characteristics:

- Households containing at least one adult member with chronic obstructive pulmonary disease (COPD)
- Households containing at least one adult member with heart disease
- Households containing at least one adult member with common mental disorder
- Households containing at least one adult member age 65 years or more
- Households in the bottom quintile of income distribution

Interventions

(1) All energy efficiency interventions (including loft insulation, double glazing, solid and cavity wall insulation, boiler replacement, and installation of gas central heating) where such measures were absent or sub-optimal

(2) Fuel subsidy at an initial value of £200 per household per year (index-linked to fuel price projections)

Comparators

The comparator for the economic modelling assumed that no interventions occur within the dwellings and, therefore, the underlying environmental conditions and exposures experienced by the household members remain unchanged.

Outcomes

- For cold; disease-specific mortality and morbidity for cardiovascular disease (including stroke and myocardial infarction), and morbidity for common mental disorder, COPD and childhood asthma;
- For ventilation changes; as for cold with the following additions: cardiopulmonary and lung cancer impact related to changes in exposure to fine particulate matter ($PM_{2.5}$) of both indoor and outdoor origin, stroke and myocardial infarction related to changes in second-hand tobacco smoke, and radon-related lung cancer;
- NHS contacts and associated costs;
- Household energy use and costs;
- Incremental cost-effectiveness ratios (ICER).

Uncertainties and sensitivity analysis

There are uncertainties associated with the multiple assumptions underpinning the economic model which have been addressed through the following methods:

- Monte Carlo simulation (for parameter uncertainties for home energy efficiency interventions only) using assumed distributions for: thermal loss improvements associated with the interventions, exposure-response functions for all exposure-outcome combinations, utility weights for each health outcome, and all associated costs;
- Specifying structural changes to the model to quantify uncertainties relating to: inclusion of ventilation-related health effects for energy efficiency intervention, the duration of common mental disorder (CMD) impacts, and the loss of life expectancy for cold-related deaths;
- Using alternative specifications for: including solid wall insulation, targeting interventions at dwellings with low energy efficiency, the level of fuel subsidy, and discount rate.

Results

The effect of home energy efficiency investments is fairly modest in terms of temperature increases. Those relating to fuel subsidy at an initial value of £200 per household per year are on average smaller still.

Most home energy efficiency interventions have ICERs exceeding £100k/ QALY if the benefits are counted in health terms alone. The one exception is the targeting of home energy efficiency containing one or more members with COPD, whose uncertain results suggest much smaller ICERs. However, home energy efficiency interventions are energy saving and the associated energy cost savings in part offset the capital investment. In calculations that include energy as well as intervention costs, the overall cost per QALY appears relatively favourable for interventions aimed at households containing someone with COPD, heart disease or age 65 years or more. The ratios do not appear to be as beneficial for households targeted on the basis of common mental disorder or low income alone.

Fuel subsidy is less cost-effective than home energy efficiency, but may be a more suitable option over shorter time frames to avoid the large capital investment costs for individuals with comparatively short life expectancy or if they expect to move home in a comparatively short period.

Cost-effectiveness ratios are slightly more favourable over a 5 year than a 42 year time horizon where people with specific diseases are targeted, probably in part because the number of disease-specific beneficiaries declines over time through death or recovery. Ratios are also improved by targeting homes in the existing stock with low energy efficiency.

Caution is required not to adversely affect indoor air quality by reducing ventilation rates during energy efficiency upgrades. However, the overall balance between positive and negative health impacts depends on the specific circumstances (e.g. local outdoor air quality, smoking vs. non-smoking households, high vs. low radon areas).

Limitations

The quantification of risks and benefits associated with home energy efficiency and fuel subsidy interventions is based on a model that entails a complex chain of assumed causal linkages. For some of those links the evidence base is limited and estimates of outcomes correspondingly uncertain. The results should therefore be interpreted as indicative only, but appear to be sufficient to allow judgement about the relative merits of broad intervention strategies.

Implications and interpretation of results

Home energy efficiency interventions appear broadly net beneficial for health if steps are taken to guard against potential adverse consequences of reduced ventilation. However, with few exceptions, such interventions cannot clearly be justified by health benefits alone, but such benefits add an additional rationale for home energy efficiency interventions which may already be justified by their energy and consequent carbon dioxide (CO_2) savings. Expected health benefits could therefore be used as a basis for targeting investments at vulnerable populations as a refinement to broader policy measures aimed at improving the energy efficiency of the housing stock in general. Fuel subsidies appear less desirable than energy efficiency interventions, though they may be an appropriate option over shorter time frames to avoid the large capital investment costs and disruption for individuals with comparatively short life expectancy. Given the likely health benefits, the modelling suggests that some contribution to the total cost of improving the energy efficiency of the housing stock by the health sector/ society may be justified.

Roles in the modelling process

Ian Hamilton, Payel Das and Mike Davies developed and implemented the building energy and environmental modelling methods. James Milner, Zaid Chalabi and Paul Wilkinson developed and implemented the health impact modelling methods. Ian Hamilton performed the intervention and energy cost calculations. James Milner, Zaid Chalabi and John Cairns performed the NHS cost calculations. James Milner and Ian Hamilton performed final model runs, including uncertainty analyses, and cost-effectiveness calculations.

Conflicts of interest

All members of the research team undertake research relevant to the subject of this review and the associated modelling work, and have received and continue to receive research funding from a range of funding organizations. These have included:

- The European Commission
- The European Climate Foundation
- UK Government departments
- The UK Research Councils (EPSRC, ESRC, MRC, NERC)
- The Wellcome Trust

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1 Introduction

This is the final part of the 2013/ 14 series of reviews and reports for NICE on excess winter death and morbidity. It is the fifth document in a series of reports and follows *Introduction to the topic*, *Factors determining vulnerability to winter- and cold-related mortality/morbidity* (review 1), *Interventions and economic studies* (review 2) and *Delivery and implementation of approaches for the prevention of excess winter deaths and morbidity* (review 3). It describes modelling work undertaken to examine the cost-effectiveness of interventions to reduce cold-related mortality and morbidity. These interventions have been determined following the advice of the Excess Winter Death (EWD) Public Health Advisory Committee (PHAC).

The cost-effectiveness of two contrasting interventions has been modelled: (i) the effect of energy efficiency (infrastructure) investment in the English housing stock and, (ii) the effect of a fuel subsidy. In each case, the intervention has been targeted at population subgroups identified as being particularly vulnerable to the effects of cold.

1.1 Aims and objectives

The aim of the project was to model the cost-effectiveness of interventions and approaches to prevent excess winter deaths, morbidity, and the health risks associated with cold weather and cold homes (including unintentional adverse consequences and outcomes). The specific interventions chosen for modelling were home energy efficiency upgrades and fuel subsidy.

The specific objectives were:

- To develop a model of cold-related health impacts based primarily on life table methods.
- To develop a model of the cost-effectiveness of home energy efficiency interventions and fuel subsidies, including adverse effects on indoor air quality.
- To assess costs and health and non-health benefits relevant to the interventions.

1.2 Research question

The specific research questions relating to the review of interventions (review 2) and development of the economic model (this report) were as follows:

- How effective are interventions and approaches to reduce excess winter deaths and morbidity and the negative health consequences of cold weather and cold homes?
- What is the comparative effectiveness of these interventions?
- How does effectiveness vary with socio-economic, demographic, health, geographic and housing characteristics?
- What are the impacts of these interventions on health inequalities?
- What impact do these interventions have on the wider determinants of health?
- What adverse effects are associated with changes to energy efficiency or costs of heating (for

example, reduced ventilation associated with increased levels of radon, overheating of homes)?

1.3 Model purpose

The third report in this series on excess winter death and morbidity (*Interventions and economic studies*) reviewed the literature on the effectiveness and cost-effectiveness of interventions to prevent cold-related mortality and morbidity. The review found that, although home energy efficiency interventions form a substantial proportion of this evidence, there is nevertheless a relatively limited body of evidence on the effectiveness of such interventions. However, the evidence suggests that energy efficiency interventions may improve the health of some population groups, notably those with respiratory (asthma, chronic obstructive pulmonary disease) and other chronic diseases, especially in the elderly and young children. Positive effects on health may include improvements in respiratory symptoms and the symptoms of other chronic illnesses, improved mental well-being, and reduced contacts with the health service. Evidence on the cost-effectiveness of interventions to reduce winter-and cold-related mortality and morbidity is comparatively small and very heterogeneous. It is difficult therefore to draw general conclusions about the balance of costs and benefits which are likely to depend on target groups, local context and the form of intervention. The available studies support the view that there are health benefits to be obtained from improvements in household energy efficiency, but if viewed solely as a means of improving health, these investments would (usually) not be justified. Once a wider range of benefits are included they appear to be worthwhile investments.

Given the lack of existing evidence on the cost-effectiveness of interventions to reduce excess winter ill-health, additional modelling work was considered to be necessary. The model which has been developed, uses data from the 2010 English Housing Survey (EHS) to identify households which contain specific types of individuals based on their health status, age and level of income, and targets interventions at those households. In the case of energy efficiency measures, the model estimates changes to the fabric and ventilation characteristics of dwellings in receipt of interventions (including loft and wall insulation, glazing replacement, and heating system improvements) and associated changes in energy demand and related environmental exposures, primarily to cold and mould. For fuel subsidies, we are aware of no previous work which has attempted to quantify the predicted health benefits. Our novel model estimates the proportion of the subsidy that could be used to increase internal temperatures and the corresponding change in temperature. The resulting changes in mortality risk are used to estimate the health impacts associated with the environmental changes. The model then estimates the costs associated with (a) the intervention, (b) changes in energy demand resulting from the intervention, and (c) changes in NHS health care contacts expected from the modelled health impacts.

The fourth report in this series (*Delivery and implementation of approaches for the prevention of excess winter deaths and morbidity*) highlighted a very limited body of evidence on methods to increase the uptake of interventions to prevent excess winter mortality and morbidity. As such, the model does not include the effects of local or national policies on the uptake of either intervention.

The modelling has also not addressed potential carbon dioxide equivalent (CO_2e) emission savings resulting from the modelled changes in energy demand. While a reasonable effort has been made to estimate energy savings, it is very unclear what the CO_2e emission factors of the supplied energy will be in the future. Approximately 80% of residential space heating energy is derived from the national gas grid, with a further 9% from oil, 5% electricity and the remainder a mixture of solid fuels and liquid gases. Although the UK Government has set out several possible investment scenarios for a future energy grid, these are still very uncertain and it is unclear the degree that overall grid emission factors will change. Therefore, in the modelling, no long-term CO_2 savings estimates are made.

2 Methods

This analysis follows guidance set out by NICE for evaluating public health interventions (NICE, 2013a, 2012a).

2.1 Analytical perspectives

Modelling the cost-effectiveness of interventions to reduce cold-related mortality and morbidity is complex and dependent on the chosen analytical perspective. There are a number of different ways in which the interventions considered here might conceivably be funded, including partial funding by various bodies. It is also possible that benefits could be experienced in different ways. Table 1 and Table 2 provide overviews for each intervention of how the costs are experienced under different perspectives. The shaded rows represent costs modelled in this report.

Table 1 - Costs experienced under different perspectives for home energy efficiency intervention

<u>Home energy efficiency</u>	**Perspective**				
	NHS	**Local authority**	**Government (including NHS and LA)**	**Householder**	**Combined (Government + householder)**
Taxation (for intervention)			(-)		-
Taxation (for transfer/administration)			(-)		-
Government expenditure (transfer)		(+)	+		+
Government expenditure (intervention)		(+)	+		+
Household expenditure (intervention)				(+)	
Health care costs	-		-		-
Social care costs	-/+	-/+	-/+		-/+
Carer costs				-	-
Work absence costs			-		-
School absence costs				(-)	-
Household expenditure (fuel)				-	-
CO_2 equivalent cost			(-)		-

Legend: + cost incurred, - cost saving, -/ + potential for cost incurred or cost saving, () possible cost

Table 2 - Costs experienced under different perspectives for fuel subsidy intervention

<u>Fuel subsidy</u>	**Perspective**				
	NHS	**Local authority**	**Government (including NHS and**	**Householder**	**Combined (Government +**

			LA)		householder)
Taxation (for intervention)			*(-)*		-
Taxation (for transfer/administration)			*(-)*		-
Government expenditure (transfer)			+		+
Government expenditure (intervention)			+		+
Household expenditure (intervention)					
Health care costs	-		-		-
Social care costs	-/+	-/+	-/+		-/+
Carer costs				-	-
Work absence costs			-		-
School absence costs				*(-)*	-
Household expenditure (fuel)				-	-
CO_2 equivalent cost			*(-)*		-

Legend: + cost incurred, - cost saving, -/ + potential for cost incurred or cost saving, () possible cost

In general, the distributions of costs for the two interventions are similar. However, there are important differences relating to the cost of funding the interventions. Home energy efficiency measures may be funded (or at least part-funded) from a number of sources, including Government, local authorities, individual householders, and energy suppliers. Fuel subsidies, on the other hand, would be likely to be funded through Government alone. Here, for consistency, we have modelling Government-funded interventions in both cases, but assuming that this could also include funding from local authorities. It should be noted that, unlike home energy efficiency, fuel subsidies simply represent financial losses to the intervention funder and gains to the householder (though there would be some resources used in making such a transfer).

Where costs have not been modelled here, the primary reason has been a lack of direct evidence of an effect due to changes in indoor winter temperatures. This is true for social care and carer costs (which may be shared by the NHS, local authorities, and householders), and costs related to absence from work or school. Our estimates of changes to health service costs do not account for effects due to increases in life expectancy (see section 2.7.3). It is unclear exactly how the interventions would impact on social care costs, though there is potential for increased costs if people live longer following the interventions.

CO_2 emissions have not been modelled because they are not currently regulated for households. The UK's CRC Energy Efficiency Scheme (CRC, formerly the Carbon Reduction Commitment) applies to large public and private organisations and their energy use. Whilst there may be wider societal cost benefits of CO_2 emission reductions for households, these are presently only captured through Energy Supplier Obligations (ESO), which are not included in our perspectives. Further, there is still uncertainty over the exact price of carbon to be set under future schemes and over the rules for capturing third party emission reductions.

A comprehensive analysis, including all relevant costs and benefits at a societal level, would require macroeconomic modelling which is outside the scope of this work. Following advice from NICE and the PHAC, we have modelled cost-effectiveness under four perspectives: (1) NHS, (2) Government (including NHS and local authorities), (3) Householder, and (4) Combined (Government + householder). Though not included here, there would also be potential costs experienced by the private sector, in particular to energy supply companies. The private sector may also benefit from reductions in work and school absence. Further, we have only modelled direct health impacts relating to changes in environmental exposures for individuals in households which receive the interventions. Additional potential health impacts, such as reduced quality-of-life experienced by carers, have not been included. As such, the estimated change in QALYs is the same for each perspective.

The four modelled perspectives are as follows:

2.1.1 NHS perspective

The NHS funds no part of the interventions and does not benefit from any resulting energy cost savings. It does, however, benefit from all costs associated with reduced use of health care services.

2.1.2 Government (including NHS and local authorities) perspective

Here, Government is assumed to pay for the interventions but not to benefit from any energy cost savings. Including local authorities in this perspective enables the possibility of funding (or at least partial funding) from local governments. Again, the NHS benefits from reduced health care use.

2.1.3 Householder perspective

The focus of this report is not on whether the interventions are cost-effective for individual householders. However, we have included a householder perspective to demonstrate the large potential benefits that can accrue to householders due to energy cost savings. In this perspective, householders receive the interventions (assumed to be provided by e.g. Government) and benefit from all the related energy cost savings.

2.1.4 Combined (government + householder) perspective

Under this perspective, all intervention costs and energy and NHS cost savings are included in the analysis. The rationale for considering Government and householders together is that they may both (potentially) fund interventions and both experience direct costs and benefits as a result. This perspective acts as an approximation to a societal perspective.

2.2 Conceptual modelling framework

Over the coming years, the English housing stock is expected to undergo a transformation in terms of energy efficiency, initiated by programmes such as Warm Home Discount, Green Deal and ECO, Energy Performance Certificates (EPCs)[1]. The mix of impacts on both costs to government and benefits to human health need to be reflected in ongoing impact and sustainability assessments.

The economic modelling approach combines a series of coupled and linked models, defined under a number of themed modules. The overall model uses a complex combination of procedures to estimate

[1] Warm Home Discount: https://www.gov.uk/the-warm-home-discount-scheme/overview
Green Deal and ECO: https://www.gov.uk/green-deal-energy-saving-measures
Energy Performance Certificates: https://www.gov.uk/buy-sell-your-home/energy-performance-certificates

the health impact through exposure changes related to the introduction of energy efficiency measures and a fuel subsidy. Many of the interventions are aimed at reducing heat loss and air leakage through the dwelling fabric and also improving the heating system. Fabric heat loss and heating system performance are both determinants of the exposure to cold (Oreszczyn et al., 2006a), while air tightness will have an effect on ventilation heat loss, and the additional exposure to indoor and outdoor air pollutants (Bone et al., 2010).

Over the past 25 years, over 16 million households have received an energy efficiency intervention that aimed to reduce energy demand through on going government programmes (Hamilton et al., 2014, 2013). Over a similar period (since winter 1997/98) Winter Fuel Payments (WFP) have been made to all households where one member is older than the female state pension age[2]. The Cold Weather Payments (CWP) has been made since 1988 to households on certain benefits to help alleviate demand for more energy during cold periods[3].

The research used to derive these procedures is based on recent and ongoing work and is evolving as methods become more sophisticated and refined as more data becomes available. Therefore, whilst every effort has been made to ensure the model inputs and assumptions are robust, the results of the model should be interpreted with a degree of caution (see 3.6 Limitations).

2.3 Population

The analyses have been performed for different household types in England. These households have been selected based on the health status of their occupants (i.e. COPD, mental health, and heart disease) and household characteristics (i.e. income level and age). The selection method uses the English Housing Survey as its base population and variables associated with the EHS household interview. The EHS Household Dataset comprises the full interview data (plus associated derived variables) for all cases where an interview has been completed – 13,300 households per annum (approximately 17,000 per annum before the EHS cost review). Household interviews were conducted using face-to-face computer assisted survey techniques. The interviews used computer-assisted personal interviewing (CAPI), which provides automatic routing and range checks. For more details see the 'English Housing Survey Technical Advice Note: Survey Overview and Methodology 2011-12 Update'[4].

Since the EHS is unlikely to represent accurately the actual prevalence of COPD, common mental disorders (CMD), or heart disease in the English population, all output results were scaled to increase or decrease the prevalence implied by the EHS to match published estimates. These adjustments were as follows:

- *COPD*
  Individuals in the EHS were assumed to have COPD if they had a long-standing history of breathing problems and were aged 45 or over (since COPD is much less prevalent at younger ages). This gave an estimated prevalence of 6.85%. The model results were adjusted downwards to match the published estimate of 5.90% for those aged 45 or above in England (APHO, 2011).

[2] Weather Fuel Payment: https://www.gov.uk/winter-fuel-payment/overview
[3] Cold Weather Payment: https://www.gov.uk/cold-weather-payment/overview
[4] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/211301/Survey_Overview_and_Methodology.pdf.

- *CMD*
  For CMD, individuals were identified through the 'Mental Health' variable in the EHS data, giving a prevalence of 2.20% in adults. In the health impact model (see section 2.6.3), mental health problems are represented by a score of 4 or above on the 12-item General Health Questionnaire (GHQ-12). According to the 2012 Health Survey for England (HSCIC, 2013) this represents approximately 15% of the population. However, we reduced this prevalence by 25% (i.e. to 11.25%) to account for false positives in GHQ-12. The results were therefore scaled upwards scaled accordingly.

- *Heart disease*
  Individuals were assumed to have heart disease if they had long-standing heart disease in the EHS data and were aged 45 or above. This gave an implied prevalence of 8.41%. Results were adjusted upwards to match the published estimate of 10.96% (APHO, 2013)

Since the model is based on a representative sample of English households, it automatically includes overlap between the target groups and this should represent the actual degree of overlap in England. For example, it is likely that the age 65+ target group will also contain a high proportion of people with COPD and heart disease since these conditions are more prevalent in older age groups. Table 3 shows the modelled target group populations and the overlap between these.

Table 3 - Overlap between target populations

Target group	**Composition of target group**				
	COPD	**Heart disease**	**CMD**	**Age 65 or above**	**Low income**
COPD	895,280	404,765	203,062	634,040	243,106
Heart disease	301,603	1,699,129	136,089	912,681	262,102
CMD	76,931	58,412	2,965,131	151,274	170,015
Age 65 or above	803,995	1,539,344	600,850	6,099,082	1,370,010
Low income	434,813	555,983	1,052,403	1,651,199	4,545,404

Since the health impact calculations are performed only for individuals in the EHS dataset (see section 2.6.3), we have added future births into the population to allow for additional benefits in future generations born after the intervention.

The model assumes that people do not move home during the follow up period. Therefore the populations receiving interventions in each target group do not change over time, except due to deaths. In reality, for the home energy efficiency intervention, there would be some dilution of the health impact as targeted individuals move to other (untreated) homes and other people (from the general population) move in to the improved dwellings. This dilution would not occur for the fuel subsidy since the payment is made to the individual rather than the dwelling. This issue is discussed further in section 3.5.3.

Further specific details of the targeting process can be found in the Appendix (section 6.2.4).

2.4 Interventions

Two types of household interventions were analysed in the economic modelling: household energy efficiency retrofits and fuel subsidies. These interventions were chosen following a review of available literature (see section 1.3 above) and discussions with the PHAC. The interventions have also been modelled in combination (i.e. home energy efficiency and fuel subsidy).

2.4.1 Household energy efficiency

Household energy efficiency interventions focus on heating systems (i.e. boiler replacement and new gas central heating systems), fabric insulation (i.e. lofts, walls and glazing), fabric infiltration control (i.e. draught stripping), and ventilation control (i.e. trickle vents and extract fans).

Heating system interventions focus on making changes to the heat delivery system and its efficiency. Boilers in gas central heating systems make up 96% of all heat systems (DECC, 2012a). The estimated mean efficiency of all UK residential boilers is 82.5% (Palmer and Cooper, 2013), with standard (i.e. non-condensing) boilers operating at approximately 75% efficiency comprising ~57% of all boilers. New condensing boilers may achieve around 90% efficiency, offering ~17% in theoretical energy savings compared to the non-condensing boilers. As with all the retrofit measures examined, the increased efficiency of the replacement boiler has the potential to deliver the same heat demand using less energy (i.e. energy savings) or to otherwise use the same energy and thus provide more heat and higher temperatures (i.e. comfort taking). A new gas central heating system would generally include installing a condensing gas boiler along with a heating supply system (e.g. room radiators). The system has the potential to deliver heating throughout the dwelling. The impact could include supplying heat to rooms that were previously unheated and to increase the efficiency of both the boiler and delivery system by replacing individual room heaters.

Fabric insulation interventions focus on reducing the heat loss through the dwelling fabric (i.e. roofs, glazing, walls). The estimated average fabric heat loss of English dwellings is 234 W/ K (Palmer and Cooper, 2013), which implies that 234 W of heating is required to maintain a 1 °C difference between the indoor and outdoor. The addition of more insulation will reduce the rate of heat flow through the fabric and also the air leakage. The insulation interventions presented in the modelling here focus on increasing the levels of insulation in the loft (where present), filling cavities (i.e. the air gap between brick walls), adding external or internal insulation to solid walls, and installing low-emissivity double glazing. Replacing single glazing with low-emissivity double glazing has the combined effect of reducing the rate of heat loss through the glass itself and low-emissivity coating and also reducing the air leakage of the surrounding casement. Glazing has a further (though not modelled) benefit of reducing the exposure to noise sources.

Draught stripping is the process of reducing air leakage around openings (i.e. doors, windows, chimneys and vents, and loft hatches). Approximately 20% of the English housing stock heat is lost through ventilation (Utley and Shorrock, 2010). The effect of draught stripping (also referred to as draught proofing) is to reduce ventilation heat losses, along with reducing the infiltration of air across the fabric. Ventilation control is achieved by introducing trickle vents (in the form of window vents) and extract fans (located in kitchens and bathrooms), which enable pollutants to be removed directly at source and during use (e.g. cooking times, times of use of bathroom). When building work is carried out on an existing building, with respect to ventilation, the work should comply with the applicable requirements of Schedule 1 to the Building Regulations, and the rest of the building should not be made less satisfactory in relation to the requirements than before the work was carried out (HM Government, 2010a).

The impact of these interventions on indoor conditions primarily relate to the thermal environment and indoor air quality. Oreszczyn et al. (2006) showed that in a sample of Warm Front homes the impact of installing a gas central heating system was an increase in temperature (standardized to an external temperature of 5 °C) by 1.61 °C (95% CI 1.03, 2.19) in the living room and 2.54 °C (95% CI 1.91, 3.16) in the bedroom, adjusting for region, month, deprivation and education, household size and age of resident modifiers (Oreszczyn et al., 2006a). Results also showed that insulation measures (loft and cavity wall insulation) increased adjusted temperatures by 0.76 °C (95% CI 0.15, 1.37) in the living room and 1.32 °C (95% CI 0.68, 1.97) in the bedroom. Though these suggest large changes in the temperature of homes following a gas central heating system, it is important to note that these are not adjusted for the efficiency of the dwelling. Further work from the Warm Front studies also showed that heating system installations had a corresponding drop in the relative humidity levels in the living room (-1.22%; 95% CI -3.22, -0.79) and bedroom (-4.02%; 95% CI -6.43, -1.61) (Oreszczyn et al., 2006b), again adjusting for region, month, deprivation, household size and dwelling efficiency modifiers. This same work also showed a minimal reduction in the energy demand associated with these interventions (Hong et al., 2006), along with a suggestion of improved thermal comfort (Hong et al., 2009).

An effect of the insulation, glazing and ventilation control interventions is to alter air change rates which in turn affect indoor air quality. In dwellings where no further ventilation controls are added, then the potential impact is an increase in the build-up and exposure to indoor generated pollutants whilst at the same time reducing the ingress of outdoor pollutants.

2.4.2 Fuel subsidy

The two fuel subsidies currently in effect in England are the Winter Fuel Payment (WFP) and the Cold Weather Payment (CWP). These fuel subsidy interventions seek to reduce heating fuel expenditure and assist in maintaining or improving thermal comfort, particularly for elderly households and those in receipt of benefits. Fuel payments are a costly and reoccurring expense. For example, in 2010/ 11 the WFP (£200 or £300 for those over 80), which is directly deposited into the householders' accounts, was estimated to be approximately £2.7 billion (IFS, 2011), making it significantly larger than the subsequent supplier obligation schemes. The WFP is not means tested, thus it is provided to all identified eligible households. The WFP has included one-off supplementary payments to address increases in fuel prices. The CWP is currently £25 for each consecutive 7 day period below 0 °C.

To date it is unclear what the impact of these housing efficiency and fuel payment interventions have been on health. It is also unclear what the cost-effectiveness or cost-benefit of these interventions are as they relate to health outcomes. Further, there is uncertainty around how much of the fuel payments are spent of fuel. An IFS study suggested that the delivery mechanisms were instrumental to how the payment was used by the household (Beatty et al., 2011). The IFS study showed that when the WFP was label, but that uncertainty exists around how much of the subsidy would be spent on fuel.

In the absence of strong direct evidence between fuel subsidy payments and changes in thermal conditions we have developed an indirect method based on empirical data of variations in heating behaviour in relation to the energy efficiency characteristics of the home. The modelling is based on a similar implementation of temperature take-back as describe in Hamilton et al (2011). The given payment is converted into potential energy savings with an associated temperature rise. In the modelling, the fuel price subsidy amount is indexed against projected fuel price rises. See section 2.6.2 for further details on the method.

2.5 Comparators

The comparator for the economic modelling is that no interventions occur within the dwellings. The basis for this approach is that over past 25 years the majority of energy efficiency retrofits have been driven by government-backed schemes or obligations (Hamilton et al., 2014; Mallaburn and Eyre, 2013; Rosenow, 2012). The focus of this modelling was not to model what government policy could or might be, but rather to focus on the costs and health and non-health outcomes related to interventions that are targeted at alleviating excess winter death.

The health impacts are driven by exposure changes. The comparator of no change therefore implies that the underlying environmental conditions and exposures experienced by the household members would be as is currently the case. As a result, there are no changes to the determinants of exposure change (i.e. changes to the building fabric and ventilation controls) and therefore no change in underlying health status or risk of disease.

2.6 Model structure

2.6.1 Household energy efficiency model

We modelled a number of housing energy efficiency retrofits that are designed to improve the energy performance of the home. Table 4 lists the energy efficiency measures used in the modelling.

Table 4 – Modelled energy efficiency measures

Component	Measures
Fabric	Lofts to 250mm
	Solid Wall Insulation
	Cavity Wall Filling
	New Double Glazing
	Install Condensing Boilers
	Install Gas Central Heating
Ventilation	Draught Stripping
	Trickle Vents
	Extract Fans

The modelling method combines a series of modules (described in more detail in the Appendix 6.2) that describe various components of the house and household population. Figure illustrates how the modules interact.

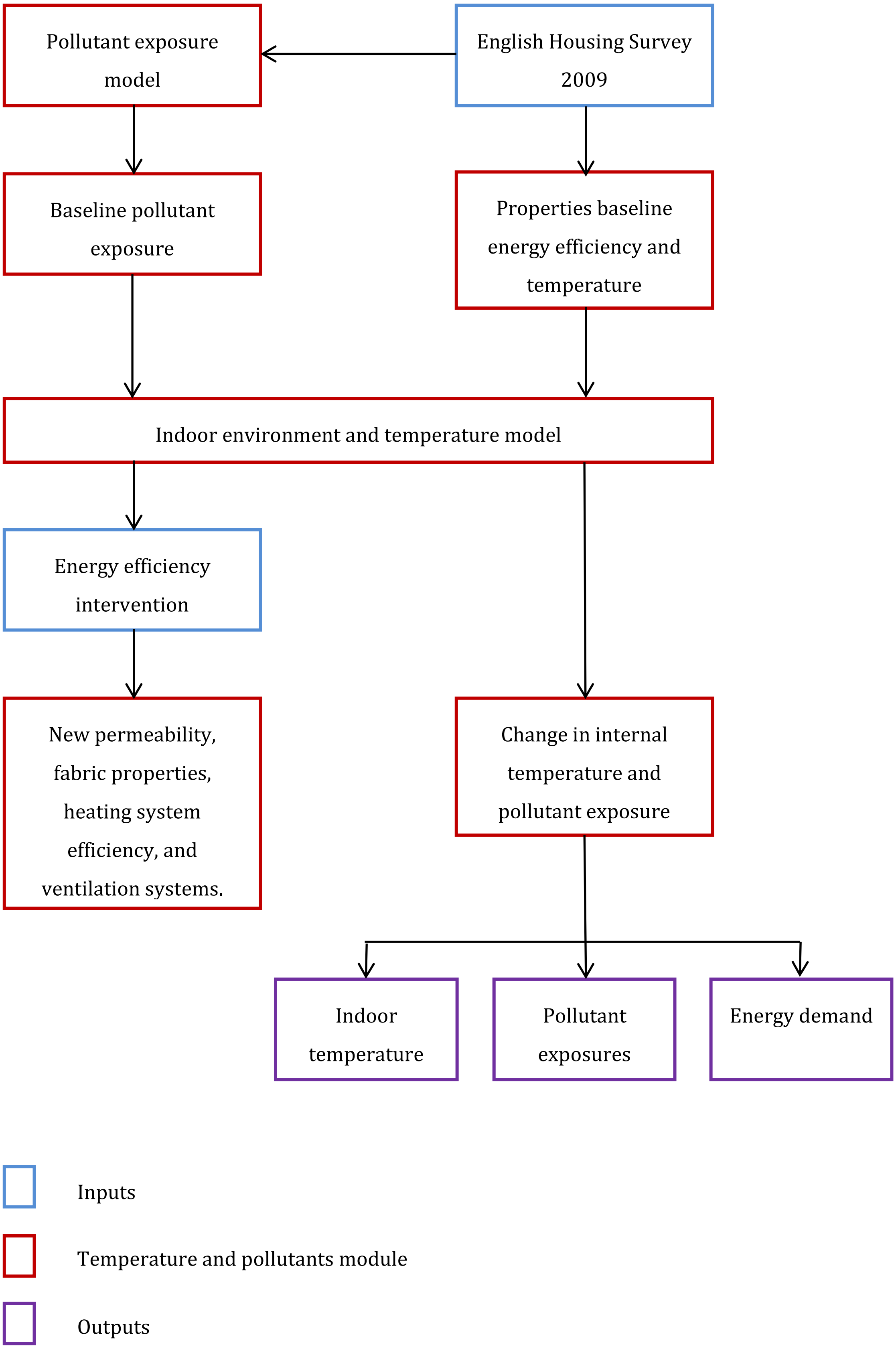

Figure 1 - Components of the housing efficiency model

The following briefly describes the purpose of the input module and the pollutant and temperature module:

Inputs

- Housing stock: The English Housing Survey (EHS) provides a baseline population that is representative of the English housing stock and households that live within. The EHS uses an un-clustered stratified sample randomly drawn from a list of all addresses in England and is updated and made available approximately every two years since 2002 (quinquennially before then, beginning in 1967) (CLG, 2013a). The survey interviews approximately 17,500 households on the details of their home and household. A further physical survey of approximately 8,000 of the interviewed houses is undertaken. The data includes approximately 16,000 variants to describe English houses.

- Household target groups: Household target groups included those with chronic obstructive pulmonary disease (COPD), heart disease, common mental disorders (CMD), elderly households (65 and older) and households in the lowest income quintile.

- Energy efficiency measures: A number of energy efficiency measures can be introduced as single or multiple measures into the model, including: loft insulation, cavity wall filling, solid wall insulation, replacement double-glazing, new condensing boiler, draught proofing, new gas central heating system, and ventilation systems (i.e. trickle vents and extract fans). The numbers of dwellings not already having had such an intervention for these measures are defined from EHS. The change in energy performance level following the measures are based on Standard Assessment Procedure (SAP) estimates and other studies related to English houses.

Building temperature and pollutants module

- Efficiency modelling: Characterises the ventilation and thermal performance of dwellings in England. It uses the DECC method of converting EHS data for use in energy models (DECC et al. 2012) and the SAP 2005 methodology for predicting the ventilation and fabric heat loss (BRE and DECC 2009).

- Pollutant modelling: Predicts the concentrations of a selection of indoor air pollutants, including: environmental tobacco smoke (ETS), indoor and outdoor sources of particulate matter <2.5 µm ($PM_{2.5}$), radon gas, and mould growth. It uses combinations of 10 building morphology archetypes (i.e. dwelling type and size) with four ventilation systems (i.e. no trickle vents or extract fans, trickle vents only, extract fans only, and both trickle vents and extract fans) and eight permeability bands. The exposure-specific diseases focused on draw on established epidemiological evidence.
    - Other health outcomes that could be related to energy efficiency interventions but were not considered here, include: cold-related falls, changes in mental health impact (aside from temperature), and some forms of indoor pollutants (e.g. volatile organic compounds (VOCs) and carbon monoxide poisoning). However, such evidence can be sparse. A particular difficult issue with many studies looking at the health effect of energy efficiency interventions is that the study designs and methods have not been sufficiently robust in their design or controlling for bias as to draw strong conclusions (Thomson et al., 2013).

- Exposure modelling: Models the change in exposure across the stock when applying energy efficiency measures. A baseline condition is predicted and a modified condition is determined through the application of the efficiency measures. The measures alter the components of the dwelling affected by the introduction of efficiency measures. The outcomes are changes in exposures.

2.6.2 Fuel subsidy model

We have developed a new method of fuel subsidies which is the first (to our knowledge) to attempt to quantify their associated health impacts and to include health in the estimation of their cost-effectiveness. Central to our model of the effect of fuel subsidies is the method for understanding what fraction of any subsidy is used by the householder to improve winter indoor temperatures (using more fuel for heating) as opposed to cost saving. The proposed method uses the empirical relationship between standardised indoor temperature (SIT)[5] and whole dwelling E-value derived by Hamilton *et al* 2011 (Figure 2). The E-value is the power (in watts) required to maintain a 1 Kelvin temperature difference between the inside and outside environment for the dwelling as a whole, and is a measure of energy efficiency (and thus relative heating cost) (Hamilton et al., 2011).

As Figure 2 shows, dwellings with high E-values (the least energy efficient homes) have the lowest indoor temperatures, and temperatures increase approximately linearly as E-values fall, i.e. with improving energy efficiency. The SIT reaches a plateau of around 18.2°C at E-values to the left of the inflexion point at around 250 W/K, suggesting that this is a temperature which the average householder living in a reasonably energy efficient home considers sufficient for comfort.

We use this curve as an indirect indication of householder behaviour. The temperature 'plateau' suggests that householders would tend not to take any subsidy as increased temperature if they are already at the energy efficient end of the E-value spectrum (below around 250 W/K). Furthermore, it suggests that the degree to which householders heat their home depends on the E-value. When the home is relatively energy inefficient (and thus heating costs relatively high), householders maintain a low average SIT; the higher the E-value, the lower the SIT. It is an assumption of this method that the primary determinant for a lower temperature is householder choice (based on cost) rather than the physical limitations of the heating system.

Our logic then proceeds as follows. There is a direct correspondence between E-value and heating cost assuming a fixed indoor temperature (SIT) and the same mix/cost of energy sources. However, for households in homes with E-values above 250 W/K the SIT *vs* E-value curve (Figure 1) suggests that householders buy more heating to increase indoor temperatures as E-values and hence relative heating costs fall.

[5] The standardised indoor temperature (SIT) is a measure of indoor temperature standardised to common measurement conditions. Specifically, it indicates the indoor temperature measured at mid-afternoon on a day when the daily maximum temperature is 5 degrees Celsius, and is based on the average of the living room and main bedroom temperature. It should be interpreted as a measure of the relative effectiveness of the heating (as measured by indoor temperature) in one dwelling compared with another.

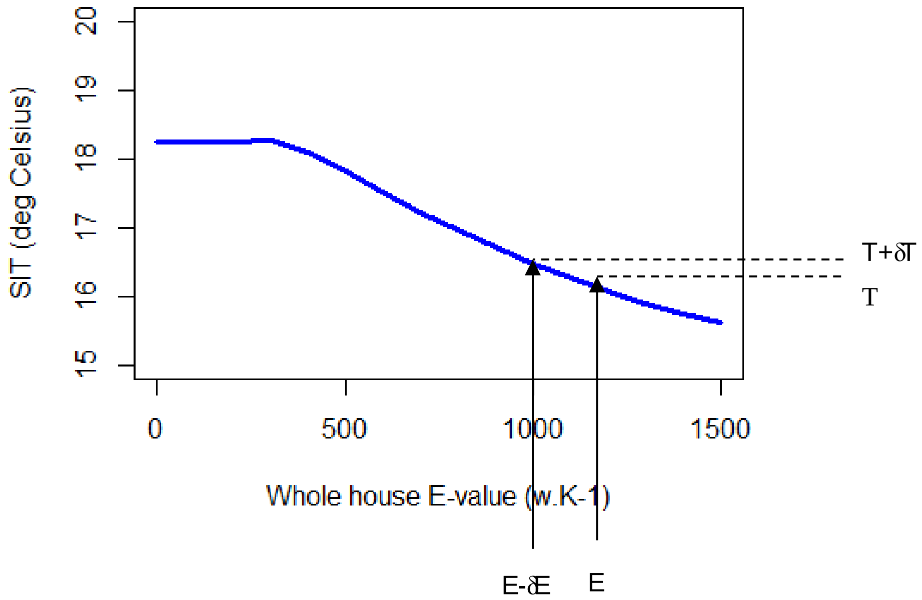

Figure 2 - Standardised indoor temperature (SIT) against whole house E-value based on the empirical data function described in Hamilton et al. (2011)

Referring to Figure 2, let δE be a left shift in E-value that delivers a given reduction, $\delta J_{(isoT)}$, in the energy (joules) required to heat the home across the year assuming no change in indoor temperature. This corresponds to translation to the left from E to E – δE parallel to the x-axis.

However, the slope of the curve above 250 W/ K suggests that a left shift of δE would be accompanied by an increase in SIT from T to T+δT. The additional energy in joules, $\delta J_{(Tincrease)}$, required to achieve this temperature increase is taken to indicate how much the average householder chooses to spend on additional heating to increase temperature given a constant temperature cost saving equivalent to δE.

The sum of $\delta J_{(Tincrease)}$ and $\delta J_{(isoT)}$ can be equated to the energy that a fuel subsidy will buy. $\delta J_{(isoT)}$ is then the energy equivalent of the subsidy the householder chooses to take as cost saving, and $\delta J_{(Tincrease)}$ the energy he/ she uses to increase the temperature of the home. Thus, the proportion of a subsidy the average householder chooses to spend on fuel to increase temperature inside the home is therefore $\delta J_{(Tincrease)}$ / ($\delta J_{(isoT)}$ + $\delta J_{(Tincrease)}$). It is this ratio that we use to indicate the apportionment of any fuel subsidy into its components contributing to (a) a warmer indoor environment and (b) cost saving, depending on the energy efficiency characteristics of the home.

2.6.3 Health impact model

Health impacts related to the interventions have been estimated using life table methods applied to the individuals in the EHS data. Individual mortality risks were based on the average for that individual's age and sex, except where the individual was identified as having COPD or heart disease. For the main analysis, assuming no change in the ventilation of dwellings, only health outcomes relevant to changes in exposure to cold and mould were considered. However, additional outcomes were modelled when accounting for the effects of changes in ventilation and resulting indoor exposures as part of the sensitivity analyses. Impacts on morbidity were estimated assuming constant ratios of morbidity to mortality for each mortality outcome. Further morbidity estimates were made using disease prevalence for two conditions which do not have substantial mortality burdens (asthma in children, mental health in adults). Impacts have been calculated both for those targeted for interventions and other individuals in the same households. For the base case scenarios, all health impacts have been discounted at a rate of 1.5%.

2.6.3.1 Impacts on mortality

The mortality impacts were calculated using a modified version of the life table model, IOMLIFET (Miller and Hurley, 2003). Life tables estimate patterns of survival in a population over time based on age-specific mortality rates. To perform a health impact assessment, the mortality rates are adjusted in response to the changed environmental exposure and the results are compared against those of the baseline (i.e. unadjusted) life table. Life tables were set up using 2010 age-specific population and (disease-specific and all-cause) mortality data for England and Wales from the Office for National Statistics (ONS), with separate life tables set up for males and females (due to their differing mortality rates and life expectancy) (ONS, 2010). For individuals identified as having COPD or heart disease, we have increased mortality risk for people with COPD (increased COPD risk) or heart disease (increased all cause risk) based on published evidence (Devereux, 2006; Peeters et al., 2002).

Exposure-response relationships for mortality were obtained from published epidemiological studies. The key relationship (SIT vs. cardiovascular mortality) is based on evidence previously covered in the second report in this series on excess winter death and morbidity (*Factors determining vulnerability to winter- and cold-related mortality/morbidity*). The other coefficients, relating mainly to ventilation-related exposures, were identified by review of the literature. The modelled exposure-response pathways and exposure-response functions are shown in Table 5.

Table 5 - Mortality outcomes modelled and exposure response relationships

Exposure	Health outcome	Exposure-response relationship	Reference
Main analysis			
Standardized internal temperature	Winter excess cardiovascular (including excess cerebrovascular accident and myocardial infarction)	0.98 per °C	Derived from (Wilkinson et al., 2001)
Sensitivity analysis (additional outcomes)			
Environmental tobacco smoke	Cerebrovascular accident	1.25 (if in same dwelling as smoker)	(Lee and Forey, 2006)
	Myocardial infarction	1.30 (if in same dwelling as smoker)	(Law et al., 1997)
$PM_{2.5}$	Cardiopulmonary	1.082 per 10 μg/ m^3	(Pope et al., 2004, 2002)
	Lung cancer	1.059 per 10 μg/ m^3	As above
Radon	Lung cancer	1.16 per 100 Bq/ m^3	(Darby et al., 2005)

Since some of the outcomes are sub-categories of others (e.g. myocardial infarction is a sub-category of cardiovascular), to avoid double counting we removed deaths in those sub-categories from the larger categories (e.g. cardiovascular does not include deaths from myocardial infarction). For outcomes affected by more than one exposure, we assumed the relative risks were multiplicative.

We have assumed no time lags for impacts resulting from changes in standardised internal temperature, as cold-related deaths are likely to begin to occur within a year. However, for the additional exposures and outcomes considered in the sensitivity analysis on the impacts of ventilation changes, a change in exposure would not lead to an immediate change in mortality in the population. For example, an increase in radon exposure would lead to almost no increase in lung cancer risk in the population for at least 10 years due to the latency period of the disease. To account for this, we incorporated disease-specific time functions to account for disease onset and cessation lags over time. The time lag functions were based on empirical evidence of the effect of smoking cessation on mortality over time (e.g. Lin et al., 2008) and expert judgment. Plots of the assumed time lag functions are shown in Figure 3.

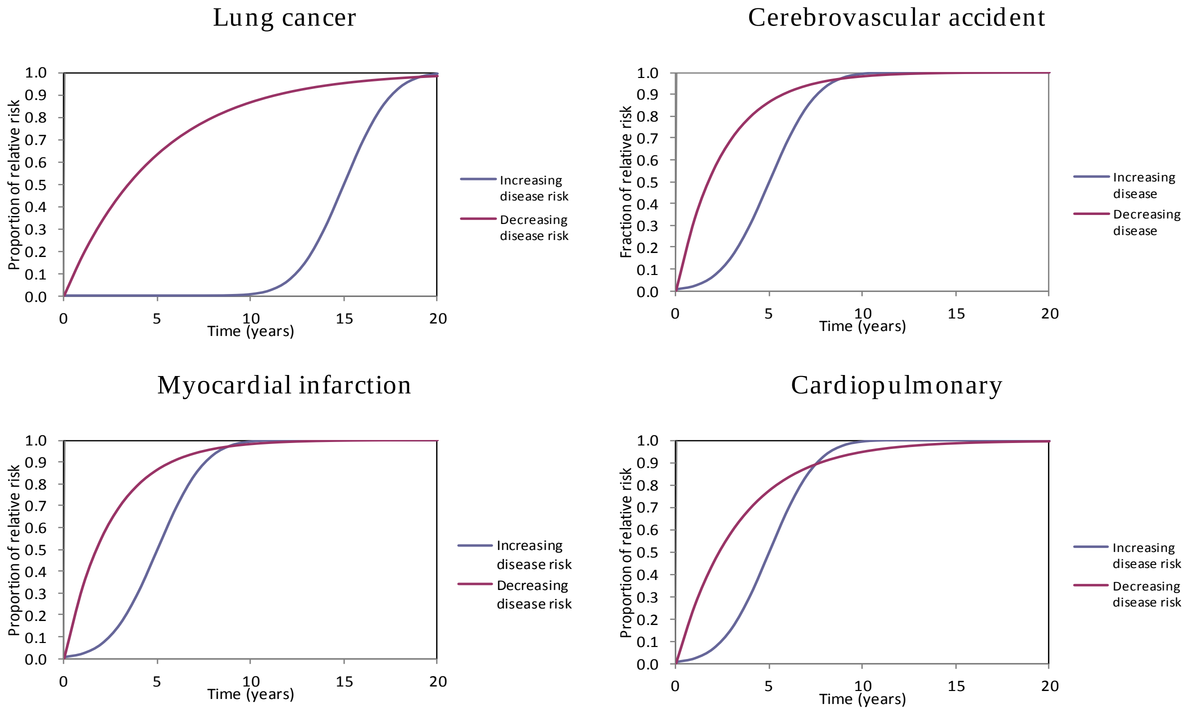

Figure 3 - Assumed time lag functions for causes of mortality related to changes in ventilation

Since the life table-based estimates are made only for individuals in the EHS dataset (representing the existing English population), we have added future births into the population to allow for additional benefits in future generations born after the intervention. The number of births each year is assumed to equal the existing population aged 0 in the survey, and these newborns experience changes in environmental exposures equal to the population-weighted mean changes.

2.6.3.2 Impacts on morbidity

Morbidity impacts were modelled using two methods depending on the condition. In the first method, estimates of changes in morbidity were made for the same outcomes as modelled for mortality. In the second, estimates of impacts on asthma in children and common mental disorder in adults were produced based on adjusting the prevalence of these conditions in the population in response to changes in standardised internal temperature and mould.

To estimate morbidity impacts associated with the mortality impacts, we assume correspondence between the burdens of morbidity and mortality for each outcome over the 42 year period. For each outcome, ratios of morbidity (hospital admissions) to mortality (deaths) were calculated using hospital admission data from Hospital Episode Statistics (HES) and mortality data from the Office for National Statistics (ONS) (Table 6). These ratios were applied to the outputs of the mortality impacts model (changes in LY over 42 years) to calculate the corresponding expected morbidity impacts.

Table 6 - Data used to estimate morbidity from mortality for each outcome

Outcome	Hospital admissions per year	Deaths per year	Ratio of morbidity to mortality
Main analysis			
Cardiovascular	937,963	133,680	7.02

COPD	135,859	25,918	5.24
Stroke	92,872	25,328	3.67
Heart attack	76,920	21,835	3.52
Sensitivity analysis (additional outcomes)			
Cardiopulmonary	1,793,984	200,545	8.95
Lung cancer	85,072	28,628	2.97

We estimated additional impacts due to (i) standardised internal temperature on mental health in adults and (ii) on COPD in adults, and due to (iii) mould on asthma in children. The calculations were performed for the individuals in the EHS identified as having these conditions. Impacts on mental health in adults, considered as the prevalence of CMD, were modelled as the proportion of the population with a 12-item General Health Questionnaire (GHQ-12) score of 4 or above. Data on CMD prevalence was taken from the Health Survey for England (HSCIC, 2013) and COPD prevalence was obtained from the Association of Public Health Observatories (APHO, 2011) (see earlier). Baseline asthma prevalence in children, taken from Asthma UK (Asthma UK, 2014), was used to represent the probability of different asthma severity in three classes using information in the Housing Health and Safety Rating System (HHSRS) (OPDM, 2003):

- Harm class II (1 out of every 110 asthma cases)
- Harm class III (16 out of every 110 asthma cases)
- Harm class IV (93 out of every 110 asthma cases)

For all morbidity outcomes, the impacts were based on exposure-response relationships obtained from published epidemiological studies (Table 7).

Table 7 - Morbidity outcome modelled and exposure response relationships

Exposure	Health outcome	Exposure-response function	
		Relative risk	Source
Standardized internal temperature (°C)	COPD	0.90 per °C	Estimate based on studies from UK (Osman et al., 2008) and New Zealand (Howden-Chapman et al., 2007)
	Mental health: Common mental disorder (GHQ-12 score 4+)	0.90 per °C	Based on Warm Front (Gilbertson et al., 2012)
Mould (% MSI > 1)	Asthma: Harm class II (hospital admission)	1.53 per 100%	Based on (Fisk et al., 2007) and used in HHSRS
	Harm class III (GP consultation)	1.53 per 100%	As above
	Harm class IV (minor symptoms)	1.83 per 100%	As above

The calculations have been performed for each appropriate individual in the EHS (identified as described previously) and their impact calculated by direct application of the exposure-response function. For both outcomes, the prevalence implied by the EHS has been compared against published prevalence estimates in England (see 2.1.6.1) and the impacts scaled accordingly. In the base case, we have assumed a constant population of children (asthma) and adults (COPD, CMD). However, for CMD, we have assumed that cold-related mental health impacts occur only during the four coldest months of the year.

The morbidity impacts were converted to quality-adjusted life years (QALYs) by weighting the estimates to account for reduced quality-of-life using utility weights from previous NICE guidance documents (Table 8). These weights did not vary by age and were chosen to represent 'average' disease status. For the broadest disease outcomes (cardiovascular, cardiopulmonary) it was not possible to obtain utility weights. As such, plausible estimates made by the modelling team were used. Although the utilities were obtained from single NICE assessments, it is acknowledged that there are variations in the utilities depending on the assessment and the stage of the disease. We have accounted for these variations in the probabilistic uncertainty analysis (see section 2.11.3).

Table 8 - Utility weights for each health outcome

Outcome	Utility weight	Source
<u>Main analysis</u>		
Cardiovascular	0.8*	
Stroke	0.736	NICE technology appraisal guidance 236 (NICE, 2011a)
Heart attack	0.812	NICE technology appraisal guidance 236
COPD	0.751	NICE technology appraisal guidance 233 (NICE, 2012b)

Common mental disorder	0.88	NICE technology appraisal guidance 97 (NICE, 2013b)
Asthma (mild)	0.97	NICE technology appraisal guidance 131 (NICE, 2012c)
Asthma (moderate)	0.85	NICE technology appraisal guidance 131
Asthma (severe)	0.669	NICE technology appraisal guidance 278 (NICE, 2013c)
Sensitivity analysis (additional outcomes)		
Cardiopulmonary	0.8*	
Lung cancer	0.53	NICE technology appraisal guidance 227 (NICE, 2011b)

*Estimate for broad outcome

The calculations are performed using average utility weights and hence do not capture the progression of disease over time. For morbidity estimates made in relation to mortality (based on the life table outputs), the duration of the utility decrement associated with the intervention is implicit in the life table results (i.e. in the variation in life year changes over time). For direct estimates of changes in disease prevalence (COPD, CMD, childhood asthma) different assumptions have been made about the duration of the decrement. For COPD and asthma, a permanent improvement in condition has been assumed. For CMD, when targeted at those with CMD, we have assumed that the prevalence in those initially targeted would fall to 50% after one year and 25% after two years, and then remain at this underlying level. This was done to account for the high likelihood of recovery within the first few years (Richards, 2011).

2.7 Resource use and costs

2.7.1 Intervention costs

2.7.1.1 Household energy efficiency

Costs associated with housing interventions are not well represented in the academic literature and most sources are available in grey and online literature and reports. For the most part, costs available from these sources have a high degree of uncertainty, as they may not define what components are included (e.g. labour, material, over-head). Further, many interventions have an associated impact on the interior decoration of the dwelling, for example replacing boiler cupboards, plaster around glazing units. They may also have a certain impact on the occupants that are not costed, such as disruption costs (i.e. temporary rehousing).

For the economic modelling, intervention costs are drawn from recent (soon to be published) DECC analysis of Warm Front, which provide costs for loft and cavity wall insulation, draught proofing, boiler replacement and gas central heating. The Warm Front programme is aimed at reducing fuel expenditure in priority households, i.e. those on benefits.

In the modelling, it is assumed that these costs represent the costs that could be paid for by other government-backed schemes. It is also assumed these costs would reflect those found within the open market. The basis of this reasoning is that many of the costs are drawn from a centralized government scheme that reflects economies of scale associated with large purchasing power. Also, the later part of the scheme was delivered under a blind competitive bidding process and therefore could represent a competitive open market.

As noted above, most intervention costs are drawn from unpublished (due to be published towards the end of April 2014) analysis of the Warm Front scheme for 2005 to 2013, carried out by members of the analysis team for the Department of Energy and Climate Change. For those costs not available from the Warm Front programme, other sources of online literature were referenced and it was assumed that the advertised costs of the measure would include material and labour costs (if not stated). No estimates of costs associated with redecorating are included in the intervention modelling.

Table 9 shows the intervention costs used for the Warm Front insulation and heat system costs. The costs are drawn from the most recent two years of the scheme, 2011/ 12 and 2012/ 13 and comprise delivery, labour and material costs associated with the intervention. These costs were collected as part of the delivery of the Warm Front scheme from the scheme administrator and represent over 60,000 data points. The data offers a range of costs that reflect the amount of material needed and the difficulty of the installation. The average of the mean values for 2011/ 12 and 2012/ 13 are used as the central estimate of costs and their standard deviations are used for probabilistic sampling.

Table 9 - Intervention costs from Warm Front (source: DECC, 2014)

Cost of measures by year	**2011/12 to 2012/13**		
Measures	**Mean**	**Median**	**Max**
Cavity Wall Insulation	430	370	1,600
Loft Insulation	330	300	1,150
Draught proofing	150	140	270
Boiler Replacement Gas	1,310	1,230	6,560
Gas Central Heating	1,520	1,470	3,180

Warm front did not cover glazing retrofits, or improvements to ventilation controls. For these costs, a review of available academic and grey sources of literature was carried out. Table 10 describes the costs, including material and labour costs. Two cost amounts were found for glazing, the costs were averaged together to represent both ranges. The values are corrected using benchmark inflation data from the Bank of England from the cited year of publication to the year 2012.

Table 10 - Intervention costs from mixed sources

Installation	**Total**	**Materials**	**Labour**	**Source(s)**
Glazing	£5,000	£3,000	£2,000	Energy Saving Trust
Glazing	£11,100	£7,800	£3,300	ETI retrofit project
Extract	£500	£250	£250	ETI retrofit project

The energy efficiency interventions described above have different life times. DECC estimate that insulation measures will last for approximately 45 years, heating measures will last for approximately 15 years, and glazing for approximately 20 years. To account for these differences, the cost of the interventions have been annualised in the form of an Equivalent Annual Cost (EAC), which is the cost of the intervention spread over the lifespan, accounting for discount rate. The total cost of all interventions has been equalised for the model period (42 years). Therefore, for shorter time periods the costs will be less than over longer periods.

2.7.1.2 Fuel subsidy

The Winter Fuel Payment of £200 is used as a basis for the fuel subsidy payment level. In order to maintain the relative change in indoor temperature resulting from the fuel subsidy over the modelling period it is necessary to maintain the purchasing power of the initial subsidy amount. To account for potential changes in subsidy amounts, the modelling links the fuel subsidy to the incremental estimated annual change in annual fuel prices over the modelled period. Therefore the fuel subsidies, being a reoccurring payment, are indexed to the change in fuel prices and are simultaneously discounted using the above mention rate of 1.5%. The cost of administering the fuel subsidy (the transfer cost) has not been included.

2.7.2 Energy costs

Energy savings are estimated using projected fuel costs from DECC. The conversion of the EHS into SAP type outputs includes price by fuel type set for 2010. These prices are proportionally increased to reflect prices in 2012 using estimates from DECC (see Table 11). In England, because the energy market is deregulated, the price paid by any household will vary depending on the supplier they choose, the payment method and any offers made. The DECC fuel prices used in the modelling are national averages, weighted by tariff type (i.e. debit, credit and prepayment) and number of regional customers. It is assumed that these estimated prices reflect those paid on average for English households.

Table 11 - Fuel Prices in 2012 (Source: DECC: DUKES 2011 table 1.1-1.6 and DECC: Quarterly Energy Prices - table 2.1.1 [1980-2012])

Fuel	Price (p/kWh)
Total solid fuels	4.43
Gas	4.62
Electricity	13.78
Oil	5.61

The economic modelling includes a 42 year time horizon. Estimates of projected retail price changes are drawn from DECC. The DECC data made estimates of retail price changes between 2012 and 2030. In order to cover the remaining 12 years, a further projection of prices was made using the TREND function in excel, which used the past prices (2010 to 2030) to project the remaining years. The projection for 2010 to 2052 is shown in Figure 4. Note the ‘kink’ in the 2033 is due to the initial rapid increase between 2010 and 2015, which then stabilises through to 2052.

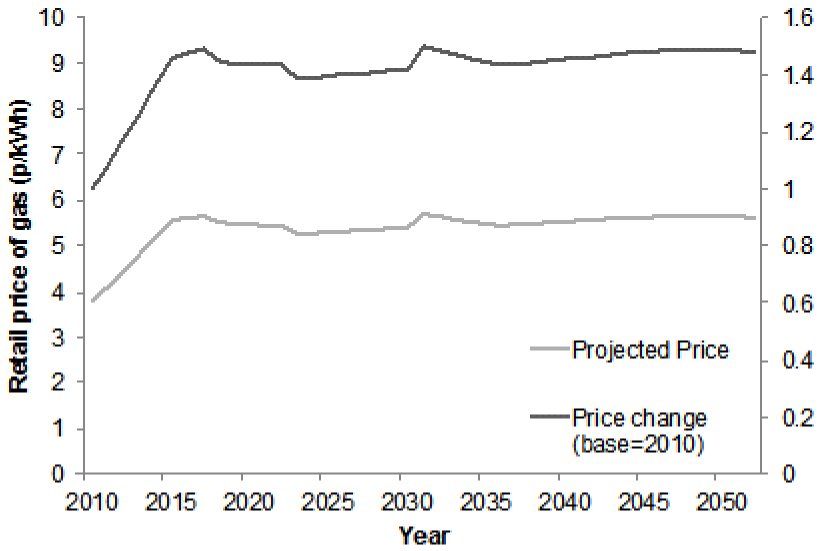

Figure 4 - DECC projected retail gas prices (Source: DECC 2012 Energy and Emissions Projections, 2012)

2.7.3 Health service costs

The life table models assume that deaths are spread evenly over the course of a year. Therefore, on average, each death results in 0.5 life years lost per year. Since this means that each life year lost per year is equivalent to two deaths, we have assumed that a ratio of hospital admissions to life years lost per year can be obtained by doubling the ratios of hospital admissions to deaths per year, shown previously in Table 6. These ratios were applied to the modelled changes in life years to estimate associated changes in hospital admissions for each outcome per year. For asthma and CMD, we assumed that changes in hospital admissions occur in proportion to the modelled change in prevalence.

We assume that the total change in hospital admissions (all outcomes combined) will result in a corresponding proportional change in total GP consultations, accounting for the proportion of all hospital admissions represented by the modelled health outcomes (based on HES data). This assumes that these health conditions make up similar proportions of total hospital admissions and total GP consultations. The most recent estimate for the total number of consultations in England is 303.9 million for 2008/ 09. However, a recent NHS report has extrapolated this figure to 2013, estimating 340 million consultations (NHS, 2013).

Unit costs for hospital admissions were taken from the National Schedule of Reference Costs 2012-13 for NHS trusts and NHS foundation trusts (see Table 12) (Dept. Health, 2013). We identified for each modelled outcome the closest equivalent Healthcare Resource Groups (HRG) codes and averaged across relevant HRGs weighted by activity (Table 12). The ranges presented were obtained using the lower and upper quartiles from the reference costs.

Table 12 - NHS reference costs and baseline hospital admissions for each outcome

Outcome	2012-13 HRG codes	Unit cost per hospital admission (£)	Baseline hospital admissions per year

		Weighted mean	Range (lower-upper quartiles)	
Main analysis				
Cardiovascular	-	£1,000*	£700*-£3,000*	937,963
Stroke	AA35A, AA35B, AA35C, AA35D, AA35E, AA35F	£3,118	£2,159-£3,530	92,872
Myocardial infarction	EB10A, EB10B, EB10C, EB10D, EB10E	£1,578	£,1179-£1,813	76,920
COPD	DZ21A, DZ21L, DZ21M, DZ21N, DZ21P, DZ21Q, DZ21R, DZ21S, DZ21T, DZ21U	£1,238	£975-£1,413	135,859
CMD (adults)	WD11Z, WD22Z, WD33Z	£1,492	£1,116-£1,703	33,481
Asthma (children)	DZ15G, DZ15H, DZ15J, DZ15K, DZ15L	£875	£684-£1,005	25,527
Sensitivity analysis (additional outcomes)				
Cardiopulmonary	-	£1,000*	£700*-£3,000*	1,793,984
Lung cancer	DZ17E, DZ17F, DZ17G, DZ17H, DZ17J, DZ17K	£1,868	£1,350-£2,193	85,072

*Estimated for broad outcome

For GP consultations, a unit cost of £45 was applied, assuming an average consultation lasting 11.7 minutes (with qualification costs) based on NHS reference costs for 2013 (Dept. Health, 2013). Since the estimates of hospital admissions and GP consultation costs are based on discounted changes in QALYs over the time frame, they are therefore implicitly discounted at the same rate of 1.5%.

2.8 Input parameters

The majority of input parameters on the English housing stock and its energy efficiency were drawn from the EHS 2010, which is the only potential source for this data. Similarly, data used to parameterise the life table models were obtained from the Office for National Statistics (ONS), again the only available source. All other input parameters were drawn from the available literature. As mentioned previously, the utility weights used in the health model were obtained from recent NICE guidance documents (agreed with NICE).

Table 13 to Table 15 presents a summary of the key input parameters used in the model and their sources. Further input parameters used in the building physics model are provided in the Appendix (6.2.5).

Table 13 – Summary of key housing model input parameters and sources

Input data		Estimate/source			
Housing stock		**Variable**	**Value**	**Unit**	**Source**
Houses	Surveyed English dwellings	Physical characteristics (age, size, type, area measurements)			English Housing Survey 2010 (CLG, 2013b)
	Surveyed English households	Household characteristics (occupants, socio-economic status)			English Housing Survey 2010 (CLG, 2013b)
Interventions	**Component**	**EHS variable**	**Estimate**	**Unit**	**Source**
Lofts to 250mm	insulation	roof uvalue	0.22	$W/m^2 K$	RdSAP v9.83 2005
	infiltration	direct adjustment	0.1	Nach	Hong et al, 2004
Wall insulation (solid external)	insulation	external wall uvalue	0.58	$W/m^2 K$	RdSAP v9.83 2005
	infiltration	direct adjustment	0.3	Nach	Hong et al, 2004
Wall insulation (cavity fill)	insulation	external wall uvalue	0.33	$W/m^2 K$	RdSAP v9.83 2005
	infiltration	direct adjustment	0.2	Nach	Hong et al, 2004
Double glazing	insulation	glazing uvalue	2	$W/m^2 K$	RdSAP v9.83 2005
	infiltration	draught stripping percentage	0.98	Nach	Hong et al, 2004
Installation of condensing boilers	efficiency	main system efficiency	93	%	RdSAP v9.83 2005
Installation of central heating	temperature	direct temperature adjustment	0.00395	°C	Warm Front
	efficiency	main system efficiency	92	%	RdSAP v9.83 2005
Draught proofing	infiltration	floor infiltration	0.1	Nach	RdSAP v9.83 2005
	infiltration	glazing draught stripping percentage	0.98	Nach	RdSAP v9.83 2005
	infiltration	direct adjustment	0.2	Nach	Hong et al, 2004

Table 14 – Summary of health model input parameters and sources

Input data	Estimate/source
Baseline health and population data	
Population	Mid-year population estimates for 2010 from the Office for National Statistics (ONS, 2011a)
Mortality	Age-specific mortality by cause for 2010 from the Office for National Statistics (ONS, 2011b)
Disease prevalence	COPD: Prevalence of 5.90% (aged 45+) according to modelled 2011 estimates from the Association of Public Health Observatories (APHO, 2011)
	Heart disease: Prevalence of 10.96% (aged 45+) according to modelled 2011 estimates from the Association of Public Health Observatories (APHO, 2013)
	CMD: Prevalence of 15% (aged 16+) based on self-reported mental health, as assessed by the General Health Questionnaire (GHQ-12) from Health Survey for England (HSE) 2012 (HSCIC, 2013)
	Asthma (children): Estimated prevalence of 1 in 11 children from Asthma UK (Asthma UK, 2014)
Hospital admissions	Based on 2012/ 13 Hospital Episode Statistics (HES) data on primary diagnosis for each outcome (HSCIC and ONS, 2013) (see also Table 3)
GP consultations	340 million consultations in 2013 estimated according to (NHS England, 2013) based on extrapolation of rates from (Hippisley-Cox and Viogradova, 2009)
Exposure-response functions	Estimates obtained by literature review (see Table 2 and Table 4)
Utility weights	Based on weights used for each outcome in recent NICE guidance and appraisal documents (see Table 5)

Table 15 – Summary of input costs and sources

Input data	Estimate/source
Intervention costs	
Home energy efficiency measures	See Table 6 and Table 7
Fuel subsidy	£200 based on existing Winter Fuel Payment in England (effects of £100 and £400 subsidies tested in sensitivity analysis)

Energy costs	See Table 8 and Figure 4
NHS health care costs	
Hospital admissions	Outcome specific hospital admission costs based on National Schedule of Reference Costs 2012-13 for NHS trusts and NHS foundation trusts (Dept. Health, 2013) (see also Table 9)
GP consultations	£45 assuming an average consultation lasting 11.7 minutes (with qualification costs). Based on National Schedule of Reference Costs 2012-13 for NHS trusts and NHS foundation trusts (Dept. Health, 2013)

2.9 Key assumptions

The most important assumptions of the economic model are detailed in the following sections.

2.9.1 Household energy efficiency model

The key assumptions of the household energy efficiency model are:

- Changes in indoor winter temperatures can be predicted using an empirical relationship between the standardized internal temperature and the whole dwelling E-value.
- The average of the standardised living room and bedroom temperatures (SIT) provides a useful estimate of heating season average whole-house temperatures.
- SIT depends exclusively on the E-value (i.e. predicted energy efficiency) of the dwelling.
- The selected archetypes are adequate to represent the variation in geometry observed in the English housing stock (Oikenoumou et al., 2010) (see Appendix 6.2.2).
- The EHS dwellings can be matched to the modelled building variants, according to rules described in the Appendix.
- For the main analysis, energy efficiency measures have no impacts on ventilation.
- All dwellings built after 1990 have trickle vents and that the 8% of dwellings built before 1990 having trickle vents is random (e.g. has no dependence on dwelling characteristics or region).
- The radon concentration is half that of ground-floor flats in first-floor flats, and zero in higher level flats.
- The behaviour of occupants, with regards to their interaction with windows, and production and removal of pollutants is assumed to depend only on the size of the dwelling.
- All ventilation and heating systems are assumed to function correctly, with no allowance made for mechanical failure or deterioration with time.
- The target groups in relation to dwelling characteristics are adequately represented by the EHS and can be identified from self-reported symptoms.
- People do not move home at any point following the intervention.

2.9.2 Fuel subsidy model

The key assumptions of the fuel subsidy model are:

- Choice in expenditure on temperature at a given level of home energy efficiency is reflected in the SIT vs E-value curve, which is assumed not to be constrained by the physical capacity of the heating system to heat the home but only by the choice of how much the heating system is used (cost).
- The unit fuel cost is the same for all dwellings (there is no direct evidence on the variation in the SIT vs E-value curve for different fuel sources/ tariffs).
- The SIT vs E-value relationship is representative of the relationship under a given fuel prices.

2.9.3 Health impact model

The key assumptions of the health impact model are:

- Health effects of changes in indoor temperature can be accurately quantified using a synthesis of evidence from a sparse number of intervention and observational studies (Table 2). In particular, evidence from time series studies relating internal winter temperatures to daily mortality can be used to quantify long-term loss of life expectancy (see section 2.11.1)
- Health effects due to changes in indoor air quality can be quantified using published epidemiological evidence of varying robustness (Table 2).
- Health impacts are modelled by changes in life expectancy and disease prevalence of a self-replenishing population.
- Mortality rates vary only with age and sex (there is no dependence on e.g. socioeconomic factors, except for individuals identified as suffering from COPD or heart disease).
- Changes in exposures affect mortality risk at all ages.
- The age- and cause- specific baseline mortality rates and disease prevalence do not change over time (i.e. constant at 2010 levels over the 42 years of follow up).
- Individuals in the EHS are only identified as having COPD or heart disease if they are aged 45 years or over (see 2.3 Population).
- Morbidity does not depend on e.g. socio-economic factors, underlying health status, etc.
- People with clinical CMD experience a recovery rate that takes the underlying prevalence to 50% after 1 year and 25% after two years, at which point the rate of natural/ treatment-related recovery and relapse are assumed to balance.
- Cold-related mental health impacts occur only during the four coldest months of the year.
- The relative risk for COPD-related symptoms is assumed to be 0.9 per °C increase in SIT, a figure which reflects unclear evidence of temperature benefit from UK COPD intervention studies, but larger impact in less relevant New Zealand intervention studies.
- Relative risks are multiplicative.

- No time lags for impacts resulting from changes in standardised internal temperature. Others (ventilation-related) are as shown in Figure 3.
- The number of births each year is equal to the existing population aged 0 in the survey, which yields a roughly constant population of children over time.
- Although the calculations are performed for the existing English population (based on the EHS), benefits also accrue to future (post-intervention) births.
- There is a fixed ratio between the burdens of morbidity and mortality for each outcome over the 42 year period (Table 3).
- The utility weights associated with each health outcome are broadly representative of the average for that outcome.
- The utility weights do not vary with age.

2.9.4 Intervention costs

The key assumptions regarding estimation of the interventions costs are:

- Costs represent the costs paid for by other government-backed schemes and within the open market.
- Advertised costs of the measure include material and labour costs (if not stated).
- VAT is additional to any stated costs.
- Intervention cost capital outlay occurs at the time of intervention without any long-term payback process.

2.9.5 Energy costs

The key assumptions regarding estimation of the energy costs are:

- Estimated prices reflect those paid on average for English households.
- Estimated changes in energy prices over the modelling period account for future energy price changes based on DECC scenario modelling.
- Energy costs are discounted using the stated discount rate of 1.5%

2.9.6 Health service costs

The key assumptions regarding estimation of the health service costs are:

- A ratio of hospital admissions to life years lost per year can be obtained.
- For asthma, COPD and CMD, changes in hospital admissions occur in proportion to the modelled change in prevalence.
- The total change in hospital admissions (all outcomes combined) will result in a corresponding proportional change in total GP consultations, accounting for the proportion of all hospital admissions represented by the modelled health outcomes.

- The modelled health conditions make up similar proportions of total hospital admissions and total GP consultations.
- There is no change in NHS unit costs over time.
- Health service costs do not account for increases in life expectancy.

2.10 Key features of the analysis

The key features of the analysis are as follows:

- Due to the relatively long time-frame of the modelled interventions, costs and benefits have been discounted at a rate of 1.5% for the base case analysis (the effect of using a 3.5% discount rate is considered as part of the sensitivity analyses).
- 42 year and 5 year time periods have been used to examine near term and long term effects within the window of the longest intervention lifetime.
- All energy efficiency measures installed in all (targeted) dwellings that the dwelling is deemed to need.
- Energy efficiency measures are assumed to be installed instantly with no phasing over time.
- The amount of the fuel subsidy (initially £200) is linked to fuel prices and hence changes over time.
- Interventions are targeted at five groups based on health status (at least one person in household), age and income.
- Health impacts have been estimated for all individuals affected by intervention, including healthy people living with targeted individuals.
- The base case analysis assumes that energy efficiency interventions are applied without affecting ventilation (which is consistent with UK Building Regulations Part F). However, the sensitivity analysis considers a scenario in which ventilation is adversely affected.

2.11 Uncertainty and sensitivity analyses

Model testing identified a number of key parameters in relation to their impact on the estimated ICERs. In response, a wide range of uncertainty and sensitivity analyses were undertaken. Several structural uncertainties were tested including accounting for changes in ventilation and indoor air quality, altering the duration of CMD impact, and altering the loss of life expectancy associated with cold-related deaths. The economic evaluation of the modelled interventions also included uncertainty analysis to account for uncertainty in the key drivers of the modelling space (i.e. inputs) that are most likely to have an effect on the health outcomes and the cost-effectiveness of the application of the intervention. Further uncertainties were dealt with through a series of deterministic sensitivity tests.

2.11.1 Structural uncertainty

The following section outlines the features that relate to structural uncertainties within the economic modelling approach and the analyses performed to test various assumptions.

Inclusion of ventilation-related health effects for energy efficiency intervention

Ventilation-related impacts on health are an important component of any housing-related intervention, even if often negative. These therefore need to be included to demonstrate the important public health message of compensating for any adverse changes on indoor air quality resulting from reductions in air exchange. A test was carried out to examine the effect of actions that did not properly ventilate the dwelling following an energy efficiency intervention. The test assumed that no mitigation measures (i.e. purpose-provided ventilation) were added to the dwellings, showing the full potential impact of increases in internal pollutants and minimised ingress of outdoor pollutants.

Duration of CMD impacts

Previous evaluations of the health impacts of home energy efficiency upgrades have studied benefits only over relatively short time periods (e.g. one year). There is currently little evidence of impacts over the longer term, for instance, on whether health benefits due to increasing indoor temperatures will persist far in to the future.

Our base case scenario assumes persistence of impacts on CMD over the entire 42 year time period, except when interventions are targeted at those with CMD (see earlier). Given the large uncertainties associated with this assumption, we have also tested an alternative scenario in which impacts in those targeted with CMD persist over the entire follow up period.

Uncertainty of indoor temperature related health impact: loss of life expectancy for cold-related deaths

The economic modelling draws on analysis by Wilkinson et al. (2001) on the change in excess winter death (as a ratio of non-winter death) due to cardiovascular disease. The relationship is from a time-series analysis of mortality data and indoor temperatures, standardised to 5 °C during the winter daytime (see Evidence Statement 3.1 in the second report in this series, *Factors determining vulnerability to winter- and cold-related mortality/morbidity*). This analysis provided a trend estimate of 2% reduction in winter: non-winter ratio of cardiovascular disease, adjusted for deprivation and variation in excess winter death (EWD) by region, per increase in indoor hall temperature. In the model, the impact of changes in standardised internal temperature is used to determine the change in EWD (Oreszczyn et al., 2006a).

Among the multiple uncertainties relating to the quantification of the impact of cold-related deaths is the loss of life expectancy associated with each cold death. In the main, cold does not induce new disease or events, but rather accelerates events (especially cardiovascular events) in people with pre-existing sub-clinical or clinical disease. For example, the additional people dying from a heart attack or stroke on cold days will be people with already established atherosclerosis in whom the effect of cold is sufficient to precipitate (early) the thrombotic obstruction of an already narrowed coronary or cerebral artery. Such a thrombotic obstruction would have been likely to occur eventually anyway, but the patho-physiological effects of cold bring about the obstruction at a point earlier than it would otherwise have occurred – with consequential clinical sequelae including death in some cases.

In consequence, it is likely that the people who die of cold-related events are people who have shorter than average life expectancy. The difficulty for modelling of cold-related QALYs is that the risks of cold-related death are determined from time-series studies from which it is impossible to determine the degree of life-shortening (i.e. loss of life expectancy). Applying relative risks for cold death derived from time-series studies to life tables makes the implicit assumption that those who die of cold are representative of the population as a whole and therefore have average age-specific life expectancy. This is almost certainly untrue given that in nearly all cases they must have pre-existing underlying disease.

To address this, we have examined the effect of assuming that those vulnerable to cold fall into a "high risk" sub-group of the population with elevated underlying risk of cardiovascular death. We then examined the shortening of remaining life expectancy in such a high risk group as a function of (i) its size as a proportion of the total population (if overall cardiovascular deaths remain the same), and (ii) the elevation of risk (relative risk) in the high risk group compared to the remainder of the population.

Table 16 - Relationship between cardiovascular high-risk group size and life expectancy

Proportion of the population in the group assumed to be at high-risk for cardiovascular events	Approx. remaining life expectancy at age 70 in high risk group* (years)	Approx. life expectancy in high risk group relative to that calculated using population average mortality rates
100% (i.e. whole population equally at risk = default of applying time-series cold relative risk to life table)	14.5	100%
10%	7.5	50%
5%	5.5	38%
1%	<3	21%

*For a given size of the high risk group (as a proportion of the total population), the life expectancy declined with the increasing relative risk for cardiovascular death in that group. However, the decline showed considerable flattening after a relative risk of around 20 or so. The results shown here are the 'effective asymptote' of life expectancy for the high risk group at high relative risk.

From Table 13 it can be seen, for example, that if the vulnerable population at risk of cold death can be assumed to be around 10% of the population, then their life expectancy will be only around half that of the population as a whole. Likewise, if the vulnerable high risk group is assumed to be 1% of the population, life expectancy would be little more than a fifth of that in the population as a whole.

Using these figures, we calculated several alternative estimates for the loss of life expectancy associated with cold-related death using life tables. The sensitivity test used three 'global' correction factors of 0.50, 0.38, and 0.21 (Table 13) to adjust the total of loss of life expectancy (and hence QALYs) corresponding to assumptions that the high risk group vulnerable to cold death is confined to 10%, 5%, and 1% of the population respectively.

2.11.2 Deterministic sensitivity analyses

A number of deterministic sensitivity analyses were undertaken as follows:

1. *Inclusion of solid wall insulation in home energy efficiency intervention*
   Solid wall insulation is an expensive intervention and may not be cost-effective purely on energy terms or on health terms along. By including solid wall insulation in the base case intervention package there was the potential to skew measures that might have been shown as having reasonable cost-effectiveness ratio. The base case analysis was therefore repeated without solid wall interventions.

2. *Baseline energy efficiency (low SAP)*
   Targeting interventions at dwellings with low energy efficiency may affect cost-effectiveness.

As such, the base case analysis was repeated for homes with SAP ratings of 30 and less.

3. *Level of subsidy in fuel subsidy intervention*
   The base case fuel subsidy intervention was repeated (i) decreasing the amount of the subsidy from £200 to £100, and (ii) increasing it to £400.

4. *Discount rate*
   The effect of increasing the discount rate from 1.5% to 3.5% was tested.

2.11.3 Probabilistic sensitivity analysis

To capture the uncertainty in the health impacts related to the input parameters, Monte Carlo uncertainty analysis has been undertaken to explore the range of uncertainty in the health impact estimates and the health service costs comprising two levels: individual level and population level. Individual level probabilistic uncertainty has been explored by sampling the primary exposure determinant (i.e. effect of intervention), exposure-response relationships and utility weights for each health outcome and intervention costs for a total of 100 iterations for the elderly (>65) target group. The number of iterations was selected to ensure a sufficiently wide variation was captured, but was small enough to allow for computational efficiency. Population level probabilistic uncertainty has been explored by sampling the health service costs, change in energy costs, and intervention costs for a total of 10,000 iterations. The uncertainty ranges of the population level were sampled from the individual level estimates for the health impacts. This two-stage uncertainty analysis provides a means of investigating the overall uncertainty from the individual level through to the population level in the model.

The end result of the uncertainty analysis was to provide incremental cost-effectiveness scatterplots, with 95% confidence ellipse to assess the uncertainty in the model. In addition, cost-effectiveness acceptability curves were plotted to demonstrate the likelihood that interventions are cost-effective at a given willingness to pay threshold.

Due to the lack of evidence, we assumed that there is no correlation between the model parameters in the Monte Carlo simulations. This will make the scatter plots of the incremental costs and incremental effectiveness in the cost-effectiveness plane more likely to be symmetrical than their counterparts in other economic evaluations (e.g. in health technology assessments). In the modelling, the interventions costs were scaled according to the amount of material needed and the size of the technology installed (i.e. more insulation or larger boilers for larger dwellings). However, these costs are independent of the potential change in exposure, which is non-linear related to the cost of the intervention. Changes in temperatures are related to the energy performance of the building and the heating system's ability to maintain a temperature difference between the indoor and outdoor environment. Changes in ventilation-related exposures are related to the physical building characteristics, such as size, height above ground, aperture openings, and operations.

Individual level uncertainty analysis

Sampling of exposure determinants

Uncertainty in the exposure-determinants (i.e. interventions) was captured by sampling from a distribution around the mean change in the physical building component associated with an intervention. The mean values were derived from the RdSAP estimates. Where no estimate of the standard error was known, a standard approach of using 10% of the parameter mean for the standard error was used, following Pavey et al. (2011). Table 17 provides the input value means, standard errors and curve type for each intervention component. Normal distributions were used for the intervention target ranges. For each dwelling variant a value was randomly sampled using the shape parameters. Due to the size of the standalone economic model (i.e. 7,000 input variants), the sampling was iterated 100 times.

Normal distributions were used to specify the uncertainty in the exposure-determinants. For heating and insulation interventions, the means were desired target levels and therefore likely to be normally distributed. For ventilation changes, there is limited available evidence and therefore normal distributions were also specified.

Table 17 - Exposure-determinant mean values and probability sampling ranges

Intervention	Component	Measure	Curve	Mean	Standard Error*
Loft insulation	Roof heat loss	u-value	normal	0.16	0.02
	Roof infiltration	ACH	normal	0.1	0.01
Cavity wall insulation	Wall u-value	u-value	normal	0.33†	0.03
	Wall infiltration	ACH	normal	0.2	0.02
Solid wall insulation	Wall u-value	u-value	normal	0.58†	0.06
	Wall infiltration	ACH	normal	0.2	0.02
Double glazing replacement	Glazing u-value	u-value	normal	1.8	0.18
	Glazing frame infiltration	% leakage	normal	0.98	0.05
Boiler replacement	Boiler	% efficiency	normal	90	3.00
Gas central heating	Heat system	% efficiency	normal	90	3.00

*10% of mean, with exception of glazing frame infiltration (5%) and heat system efficiency (3%)
†An average across SAP dwelling ages

Sampling of exposure-response functions

Using a similar approach to the interventions, shape parameters were defined for each exposure-outcome pathway using estimates of 95% confidence intervals (CI) from the original source references, where available. Normal distributions based on the CI of the central estimates were used for the relative risks; however, where the uncertainty was great or the evidence was limited, uniform distributions (i.e. uninformative prior) over an appropriate range were used. Normal distributions were applied to the relative risks associated with cardiovascular disease, common mental disorder, and asthma. A uniform distribution was applied to that of COPD.

Sampling of utility weights

Since there is variation in the utilities within each disease category, utility weights for morbidity estimates were sampled using uniform distributions with +/ - 10% as the upper and lower level ranges. These were applied to CVD, stroke, heart attack, COPD, CMD, and asthma.

Sampling of costs

Individual-level intervention costs were sampled using cost data for each intervention type. Gamma distributions were used for the intervention cost ranges, with standard deviations drawn from the literature where available and +/ - 10% of the mean used in the absence of evidence. Because costs are limited to a zero lower boundary and are often right skewed, gamma distributions were used to specify the uncertainty in the mean costs.

Population level uncertainty analysis

The individual level uncertainty analysis was used to derive uncertainty ranges around the total health impacts, intervention costs, and changes in energy demand. Normal distributions were used for health impacts and changes in energy demand with the mean and standard deviation drawn from the individual level analysis. Population level uncertainty ranges were also applied to the health care (hospital episode and GP consultation) contact costs (by disease, where relevant), and fuel costs. Gamma distributions were used for health care and fuel costs.

The uncertainty analysis was performed for a sample of 10,000 iterations and was used in examining the incremental cost-effectiveness of the interventions to healthcare outcomes. Incremental cost effectiveness ratios (ICER) were derived for each of the defined perspectives.

2.12 Internal validation

The quality of the economic model was assessed during its development using the following steps:

- Regular scenario testing was performed by two independent members of the modelling team (i.e. not directly involved in model development) to identify errors;
- Regular assessment and checking of model outputs was performed by the wider modelling team;
- Intermediate output results from the model (e.g. dwelling permeabilities and fabric heat losses, exposure changes) were compared against available literature and other published estimates (see section 3.3 Validation);
- Outputs from the health impact model were continuously checked against the (commonly used) IOMLIFET model, on which the calculations are based, to ensure consistency between the two models;
- Pollutant exposure model runs used CONTAMv2.4c, a validated multi-zone airflow and pollutant transport simulation tool (Emmerich, 2001; Haghighat and Li, 2004; Walton and Dols, 2006), and were internally validated against published sources (Shrubsole et al., 2012).
- The energy efficiency model was parameterized using the SAP approach and EHS data (DECC et al., 2012), the outputs of these data were compared against published data in the Great Britain Energy Fact File (Palmer and Cooper, 2012).
- Extensive uncertainty and sensitivity analyses have been performed to test the validity of the model with respect to its input parameters (see sections 2.11.2-2.11.3 and 3.2.2-3.2.3) and several key structural assumptions (see sections 2.11.1 and 3.2.1).

3 Results

3.1 Base-case analysis

The base case analysis assumes no changes in dwelling ventilation as a result of the interventions. The results are summarised in the following sections. In all tables, note that negative signs indicate incremental reductions/ cost savings relative to the counterfactual.

3.1.1 Costs and benefits of household energy efficiency intervention

Table 18 and Table 19 summarise the modelled costs and benefits in the base case analysis for installation of home energy efficiency measures for different population subgroups over 5 and 42 years.

Table 18 - Summary of base case costs and benefits for home energy efficiency intervention over 5 years

Intervention	All energy efficiency measures installed in eligible homes				
Description					
Time frame	5 years	5 years	5 years	5 years	5 years
Population	Households containing at least one person with:				
Target group	COPD	heart disease	CMD	age 65 or above	low income
Number of affected households	1,003,853	1,789,366	3,641,674	4,869,389	3,409,304
Size of affected population	2,211,431	2,741,572	3,965,976	7,258,132	6,168,686
Mean changes in environmental exposures					
Standardised internal temperature (°C)	+0.29 °C	+0.35 °C	+0.26 °C	+0.39 °C	+0.23 °C
Mould (% MSI > 1)	-0.46%	-0.54%	-0.38%	-0.64%	-0.33%
Intervention cost					
Number of interventions	1,778,439	3,185,491	6,713,955	8,677,392	6,126,532
Total cost of intervention (M£)	£1,382	£2,624	£5,466	£7,338	£4,893
Energy cost					
Total change in stock energy demand (GWh/ yr)	-6,199	-11,448	-23,105	-33,551	-19,502
Total incremental energy cost (M£)	-£1,192	-£2,278	-£4,344	-£6,643	-£3,860
NHS healthcare cost					
Change in healthcare contacts					
- GP consultations	-187,711	-166,243	-32,772	-675,854	-179,535
- Hospital admissions	-8,362	-7,405	-1,460	-30,107	-7,998
Cost of healthcare contacts					
- GP consultations (M£)	-£8	-£7	-£1	-£30	-£8
- Hospital admissions (M£)	-£11	-£10	-£2	-£39	-£10
Total incremental NHS health care cost (M£)	-£19	-£17	-£3	-£69	-£18
QALYs gained					
Cardiovascular	1,148	2,179	394	9,903	2,594
Stroke	182	341	61	1,495	365
Heart attack	177	341	60	1,620	442
Common mental disorders	3,735	1,637	10,732	7,485	6,618
COPD	42,751	12,071	2,479	25,513	7,402
Asthma (children)	135	19	119	84	246
Total QALYs gained	48,129	16,588	13,845	46,100	17,668

Table 19 - Summary of base case costs and benefits for home energy efficiency intervention over 42 years

Intervention	All energy efficiency measures installed in eligible homes				
Description					
Time frame	42 years	42 years	42 years	42 years	42 years
Population	Households containing at least one person with:				
Target group	COPD	heart disease	CMD	age 65 or above	low income
Number of affected households	1,003,853	1,789,366	3,641,674	4,869,389	3,409,304
Size of affected population	2,211,431	2,741,572	3,965,976	7,258,132	6,168,686
Mean changes in environmental exposures					
Standardised internal temperature (°C)	+0.29 °C	+0.35 °C	+0.26 °C	+0.39 °C	+0.23 °C
Mould (% MSI > 1)	-0.46%	-0.54%	-0.38%	-0.64%	-0.33%
Intervention cost					
Number of interventions	1,778,439	3,185,491	6,713,955	8,677,392	6,126,532
Total cost of intervention (M£)	£11,611	£22,038	£45,913	£61,635	£41,099
Energy cost					
Total change in stock energy demand (GWh/ yr)	-6,199	-11,448	-23,105	-33,551	-19,502
Total incremental energy cost (M£)	-£9,252	-£17,680	-£33,718	-£51,558	-£29,959
NHS healthcare cost					
Change in healthcare contacts					
- GP consultations	-2,325,402	-1,998,586	-861,991	-9,363,649	-2,688,512
- Hospital admissions	-103,587	-89,029	-38,398	-417,113	-119,762
Cost of healthcare contacts					
- GP consultations (M£)	-£105	-£90	-£39	-£421	-£121
- Hospital admissions (M£)	-£132	-£115	-£50	-£535	-£154
Total incremental NHS health care cost (M£)	-£237	-£205	-£89	-£957	-£275
QALYs gained					
Cardiovascular	25,626	29,187	13,304	146,198	41,919
Stroke	3,883	4,387	2,108	20,699	6,131
Heart attack	4,136	4,811	2,004	24,818	6,803
Common mental disorders	24,208	10,607	43,032	48,504	42,887
COPD	277,051	78,229	16,062	165,340	47,970
Asthma (children)	873	126	771	544	1,597
Total QALYs gained	335,776	127,346	77,281	406,104	147,308

3.1.2 Costs and benefits of fuel subsidy intervention

Table 20 and Table 21 summarise the results of the base case analysis for the fuel subsidy intervention for different population subgroups.

Table 20 - Summary of base case costs and benefits for fuel subsidy intervention over 5 years

Intervention					
Description	**Fuel subsidy of £200**				
Time frame	5 years	5 years	5 years	5 years	5 years
Population	Households containing at least one person with:				
Target group	COPD	heart disease	CMD	age 65 or above	low income
Number of affected households	1,254,640	2,199,919	4,478,555	5,906,810	4,121,007
Size of affected population	2,474,107	3,062,277	4,523,800	8,286,200	6,546,032
Mean changes in environmental exposures					
Standardised internal temperature (°C)	+0.17 °C	+0.18 °C	+0.16 °C	+0.20 °C	+0.13 °C
Mould (% MSI > 1)	-0.27%	-0.28%	-0.24%	-0.33%	-0.20%
Intervention cost					
Number of interventions	1,248,823	2,190,395	4,444,335	5,880,701	4,088,345
Total cost of intervention (M£)	£1,423	£2,496	£5,065	£6,701	£4,659
Energy cost					
Total change in stock energy demand (GWh/ yr)	984	1,906	3,170	5,526	2,292
Total incremental energy cost (M£)	-£1,243	-£2,142	-£4,487	-£5,667	-£4,234
NHS healthcare cost					
Change in healthcare contacts					
- GP consultations	-144,318	-116,598	-26,561	-441,846	-116,111
- Hospital admissions	-6,429	-5,194	-1,183	-19,682	-5,172
Cost of healthcare contacts					
- GP consultations (M£)	-£6	-£5	-£1	-£20	-£5
- Hospital admissions (M£)	-£8	-£7	-£2	-£25	-£7
Total incremental NHS health care cost (M£)	-£15	-£12	-£3	-£45	-£12
QALYs gained					
Cardiovascular	912	1,466	318	6,335	1,596
Stroke	143	229	47	960	231
Heart attack	142	230	50	1,037	270
Common mental disorders	2,133	1,421	7,258	4,503	4,128
COPD	32,282	9,829	2,151	19,755	6,548
Asthma (children)	104	18	117	25	205
Total QALYs gained	35,715	13,192	9,941	32,616	12,977

Table 21 - Summary of base case costs and benefits for fuel subsidy intervention over 42 years

Intervention	Fuel subsidy of £200				
Description					
Time frame	42 years	42 years	42 years	42 years	42 years
Population	Households containing at least one person with:				
Target group	COPD	heart disease	CMD	age 65 or above	low income
Number of affected households	1,254,640	2,199,919	4,478,555	5,906,810	4,121,007
Size of affected population	2,474,107	3,062,277	4,523,800	8,286,200	6,546,032
Mean changes in environmental exposures					
Standardised internal temperature (°C)	+0.17 °C	+0.18 °C	+0.16 °C	+0.20 °C	+0.13 °C
Mould (% MSI > 1)	-0.27%	-0.28%	-0.24%	-0.33%	-0.20%
Intervention cost					
Number of interventions	1,248,823	2,190,395	4,444,335	5,880,701	4,088,345
Total cost of intervention (M£)	£11,046	£19,374	£39,310	£52,015	£36,162
Energy cost					
Total change in stock energy demand (GWh/ yr)	984	1,906	3,170	5,526	2,292
Total incremental energy cost (M£)	-£9,644	-£16,622	-£34,824	-£43,987	-£32,867
NHS healthcare cost					
Change in healthcare contacts					
- GP consultations	-1,709,072	-1,354,556	-582,100	-5,964,912	-1,817,559
- Hospital admissions	-76,132	-60,340	-25,930	-265,713	-80,965
Cost of healthcare contacts					
- GP consultations (M£)	-£77	-£61	-£26	-£268	-£82
- Hospital admissions (M£)	-£97	-£78	-£34	-£341	-£104
Total incremental NHS health care cost (M£)	-£174	-£139	-£60	-£609	-£186
QALYs gained					
Cardiovascular	18,594	19,296	8,846	92,087	27,867
Stroke	2,796	2,894	1,383	12,953	4,046
Heart attack	3,025	3,189	1,347	15,774	4,595
Common mental disorders	13,823	9,207	29,101	29,184	26,751
COPD	209,203	63,696	13,940	128,024	42,436
Asthma (children)	671	116	761	164	1,331
Total QALYs gained	248,113	98,398	55,379	278,187	107,026

3.1.3 Combined household energy efficiency and fuel subsidy

Table 22 and Table 23 summarise the results of the base case analysis for the fuel subsidy intervention for different population subgroups.

Table 22 - Summary of base case costs and benefits for the combined home energy efficiency and fuel subsidy intervention over 5 years

Intervention	All energy efficiency measures installed in eligible homes and fuel subsidy of £200				
Description					
Time frame	5 years	5 years	5 years	5 years	5 years
Population	Households containing at least one person with:				
Target group	COPD	heart disease	CMD	age 65 or above	low income
Number of affected households	1,254,640	2,199,919	4,478,555	5,906,810	4,121,007
Size of affected population	2,541,705	3,176,405	4,712,212	8,512,024	6,998,593
Mean changes in environmental exposures					
Standardised internal temperature (°C)	+0.40 °C	+0.45 °C	+0.36 °C	+0.51 °C	+0.32 °C
Mould (% MSI > 1)	-0.51%	-0.58%	-0.44%	-0.70%	-0.38%
Intervention cost					
Number of interventions	3,027,262	5,375,886	11,158,290	14,558,093	10,214,877
Total cost of intervention (M£)	£2,805	£5,120	£10,530	£14,039	£9,552
Energy cost					
Total change in stock energy demand (GWh/ yr)	-5,491	-10,079	-20,862	-29,612	-17,949
Total incremental energy cost (M£)	-£2,485	-£4,520	-£9,000	-£12,608	-£8,230
NHS healthcare cost					
Change in healthcare contacts					
- GP consultations	-325,577	-277,544	-58,295	-1,096,970	-290,140
- Hospital admissions	-14,503	-12,363	-2,597	-48,866	-12,925
Cost of healthcare contacts					
- GP consultations (M£)	-£15	-£12	-£3	-£49	-£13
- Hospital admissions (M£)	-£18	-£16	-£3	-£63	-£17
Total incremental NHS health care cost (M£)	-£33	-£28	-£6	-£112	-£30
QALYs gained					
Cardiovascular	2,025	3,578	700	15,941	4,113
Stroke	319	559	106	2,410	584
Heart attack	314	561	108	2,608	699
Common mental disorders	5,777	3,002	17,643	11,771	10,538
COPD	73,479	21,454	4,547	44,354	13,690
Asthma (children)	178	27	171	90	326
Total QALYs gained	82,092	29,182	23,276	77,174	29,950

Table 23 - Summary of base case costs and benefits for the combined home energy efficiency and fuel subsidy intervention over 42 years

Intervention					
Description	**All energy efficiency measures installed in eligible homes and fuel subsidy of £200**				
Time frame	42 years	42 years	42 years	42 years	42 years
Population	Households containing at least one person with:				
Target group	COPD	heart disease	CMD	age 65 or above	low income
Number of affected households	1,254,640	2,199,919	4,478,555	5,906,810	4,121,007
Size of affected population	2,541,705	3,176,405	4,712,212	8,512,024	6,998,593
Mean changes in environmental exposures					
Standardised internal temperature (°C)	+0.40 °C	+0.45 °C	+0.36 °C	+0.51 °C	+0.32 °C
Mould (% MSI > 1)	-0.51%	-0.58%	-0.44%	-0.70%	-0.38%
Intervention cost					
Number of interventions	3,027,262	5,375,886	11,158,290	14,558,093	10,214,877
Total cost of intervention (M£)	£22,657	£41,413	£85,224	£113,650	£77,260
Energy cost					
Total change in stock energy demand (GWh/ yr)	-5,491	-10,079	-20,862	-29,612	-17,949
Total incremental energy cost (M£)	-£19,291	-£35,084	-£69,855	-£97,857	-£63,883
NHS healthcare cost					
Change in healthcare contacts					
- GP consultations	-3,958,309	-3,290,581	-1,418,508	-15,047,896	-4,424,885
- Hospital admissions	-176,327	-146,582	-63,189	-670,323	-197,111
Cost of healthcare contacts					
- GP consultations (M£)	-£178	-£148	-£64	-£677	-£199
- Hospital admissions (M£)	-£225	-£189	-£82	-£860	-£254
Total incremental NHS health care cost (M£)	-£403	-£337	-£146	-£1,537	-£453
QALYs gained					
Cardiovascular	43,430	47,591	21,763	233,961	68,542
Stroke	6,558	7,146	3,430	33,032	9,994
Heart attack	7,033	7,852	3,292	39,847	11,194
Common mental disorders	37,437	19,457	70,744	76,285	68,293
COPD	476,181	139,033	29,467	287,435	88,716
Asthma (children)	1,156	177	1,111	581	2,114
Total QALYs gained	571,795	221,255	129,808	671,142	248,853

3.1.4 Summary of incremental cost-effectiveness ratios for base case

Table 24 and Table 25 provide summaries of per household costs, benefits and ICERs over the two modelled time frames for different perspectives (see section 2.1 for details)

Table 24 – Summary of per household costs and benefits and incremental cost-effectiveness ratios for all base case scenarios over 5 years

		All energy efficiency interventions					£200 fuel subsidy					All energy efficiency interventions + £200 fuel subsidy				
5 year time horizon (per household)		COPD	Heart disease	CMD	Age 65+	Low income	COPD	Heart disease	CMD	Age 65+	Low income	COPD	Heart disease	CMD	Age 65+	Low income
A	Number of people	2.20	1.53	1.09	1.49	1.81	1.97	1.39	1.01	1.40	1.59	2.03	1.44	1.05	1.44	1.70
B	Number of interventions	1.77	1.78	1.84	1.78	1.80	1.00	1.00	0.99	1.00	0.99	2.41	2.44	2.49	2.46	2.48
C	Change in energy demand (kWh/ yr)	-6,175	-6,398	-6,345	-6,890	-5,720	784	866	708	936	556	-4,377	-4,582	-4,658	-5,013	-4,355
D	Total QALYS/ 10^3	47.94	9.27	3.80	9.47	5.18	28.47	6.00	2.22	5.52	3.15	65.43	13.26	5.20	13.07	7.27
	Cardiovascular (incl stroke + MI)	1.50	1.60	0.14	2.67	1.00	0.95	0.88	0.09	1.41	0.51	2.12	2.14	0.20	3.55	1.31
	Common mental disorders	3.72	0.91	2.95	1.54	1.94	1.70	0.65	1.62	0.76	1.00	4.60	1.36	3.94	1.99	2.56
	COPD	42.59	6.75	0.68	5.24	2.17	25.73	4.47	0.48	3.34	1.59	58.57	9.75	1.02	7.51	3.32
	Asthma (children)	0.13	0.01	0.03	0.02	0.07	0.08	0.01	0.03	0.00	0.05	0.14	0.01	0.04	0.02	0.08
E	Intervention costs (£)	1,377	1,466	1,501	1,507	1,435	1,134	1,135	1,131	1,135	1,131	2,236	2,327	2,351	2,377	2,318
F	Change in energy costs (£)	-1,187	-1,273	-1,193	-1,364	-1,132	-990	-973	-1,002	-959	-1,028	-1,981	-2,055	-2,010	-2,134	-1,997
G	Change in NHS health care costs (£)	-19	-10	-1	-14	-5	-12	-5	-1	-8	-3	-26	-13	-1	-19	-7
Incremental cost-effectiveness ratios (£/QALY)																
	NHS (G/ D)	-£395	-£1,027	-£243	-£1,503	-£1,037	-£409	-£905	-£274	-£1,388	-£914	-£402	-£974	-£257	-£1,457	-£989
	Government (incl NHS+LA) (E+G)/ D	£28,324	£157,137	£394,556	£157,661	£275,896	£39,437	£188,301	£509,205	£204,076	£358,089	£33,771	£174,467	£452,154	£180,456	£317,927
	Householder (F/ D)	-£24,767	-£137,318	-£313,779	-£144,089	-£218,468	-£34,790	-£162,332	-£451,333	-£173,750	-£326,296	-£30,275	-£154,892	-£386,653	-£163,365	-£274,804
	Combined (E+F+G)/ D	£3,557	£19,819	£80,777	£13,572	£57,429	£4,647	£25,969	£57,872	£30,325	£31,793	£3,496	£19,575	£65,502	£17,091	£43,123

Table 25 – Summary of per household costs and benefits and incremental cost-effectiveness ratios for all base case scenarios over 42 years

	All energy efficiency interventions					£200 fuel subsidy					All energy efficiency interventions + £200 fuel subsidy				
42 year time horizon (per household)	COPD	Heart disease	CMD	Age 65+	Low income	COPD	Heart disease	CMD	Age 65+	Low income	COPD	Heart disease	CMD	Age 65+	Low income
A Number of people	2.20	1.53	1.09	1.49	1.81	1.97	1.39	1.01	1.40	1.59	2.03	1.44	1.05	1.44	1.70
B Number of interventions	1.77	1.78	1.84	1.78	1.80	1.00	1.00	0.99	1.00	0.99	2.41	2.44	2.49	2.46	2.48
C Change in energy demand (kWh/ yr)	-6,175	-6,398	-6,345	-6,890	-5,720	784	866	708	936	556	-4,377	-4,582	-4,658	-5,013	-4,355
D Total QALYS/ 10^3	334.49	71.17	21.22	83.40	43.21	197.76	44.73	12.37	47.10	25.97	455.74	100.57	28.98	113.62	60.39
Cardiovascular (incl stroke + MI)	33.52	21.45	4.78	39.37	16.09	19.46	11.54	2.58	20.45	8.86	45.45	28.45	6.36	51.95	21.77
Common mental disorders	24.11	5.93	11.82	9.96	12.58	11.02	4.19	6.50	4.94	6.49	29.84	8.84	15.80	12.91	16.57
COPD	275.99	43.72	4.41	33.95	14.07	166.74	28.95	3.11	21.67	10.30	379.54	63.20	6.58	48.66	21.53
Asthma (children)	0.87	0.07	0.21	0.11	0.47	0.54	0.05	0.17	0.03	0.32	0.92	0.08	0.25	0.10	0.51
E Intervention costs (£)	£11,566	£12,316	£12,608	£12,658	£12,055	£8,804	£8,807	£8,777	£8,806	£8,775	£18,058	£18,825	£19,029	£19,241	£18,748
F Change in energy costs (£)	-£9,217	-£9,881	-£9,259	-£10,588	-£8,787	-£7,687	-£7,556	-£7,776	-£7,447	-£7,976	-£15,375	-£15,948	-£15,598	-£16,567	-£15,502
G Change in NHS health care costs (£)	-£236	-£114	-£24	-£196	-£81	-£139	-£63	-£13	-£103	-£45	-£321	-£153	-£33	-£260	-£110
Incremental cost-effectiveness ratios (£/QALY)															
NHS (G/ D)	-£706	-£1,608	-£1,149	-£2,355	-£1,868	-£702	-£1,410	-£1,081	-£2,189	-£1,737	-£705	-£1,523	-£1,125	-£2,290	-£1,820
Government (incl NHS+LA) (E+G)/ D	£33,873	£171,452	£592,955	£149,417	£277,131	£43,818	£195,487	£708,765	£184,790	£336,141	£38,918	£185,648	£655,412	£167,049	£308,647
Householder (F/ D)	-£27,555	-£138,836	-£436,308	-£126,959	-£203,376	-£38,870	-£168,931	-£628,833	-£158,119	-£307,096	-£33,737	-£158,567	-£538,142	-£145,807	-£256,712
Combined (E+F+G)/ D	£6,318	£32,616	£156,646	£22,458	£73,755	£4,948	£26,556	£79,931	£26,671	£29,045	£5,181	£27,081	£117,270	£21,242	£51,935

3.2 Uncertainty and sensitivity analyses

3.2.1 Structural uncertainty

Structural uncertainty 1: Inclusion of ventilation-related health effects for energy efficiency intervention

The base case was repeated but allowing for changes in dwelling ventilation due to the increased airtightness that would be expected following energy efficiency upgrades. This will affect various indoor exposures, including indoor- and outdoor-generated $PM_{2.5}$, environmental tobacco smoke and radon. Modelled estimates of the resulting changes in exposures, assuming no compensatory purpose-provided ventilation, are shown in Table 26.

Table 26 - Modelled mean changes in indoor air exposures for different scenarios

	Mean changes in environmental exposures				
Target group:	COPD	Heart disease	CMD	Age 65 or above	Low income
Base case					
Standardised internal temperature (°C)	+0.29 °C	+0.35 °C	+0.26 °C	+0.39 °C	+0.23 °C
Mould (% MSI > 1)	-0.46%	-0.54%	-0.38%	-0.64%	-0.33%
$PM_{2.5}$ from outdoor sources (µg/ m^3)	-	-	-	-	-
$PM_{2.5}$ from indoor sources (µg/ m^3)	-	-	-	-	-
Environmental tobacco smoke*	-	-	-	-	-
Radon (Bq/ m^3)	-	-	-	-	-
Including ventilation changes					
Standardised internal temperature (°C)	+0.32 °C	+0.37 °C	+ 0.28 °C	+0.42 °C	+0.24 °C
Mould (% MSI > 1)	+1.00%	+0.85%	+1.02%	+0.78%	+1.26%
$PM_{2.5}$ from outdoor sources (µg/ m^3)	-0.51	-0.52	-0.53	-0.53	-0.52
$PM_{2.5}$ from indoor sources (µg/ m^3)	+0.65	+0.67	+0.67	+0.71	+0.69
Environmental tobacco smoke*	+0.06	+0.04	+0.11	+0.04	+0.10
Radon (Bq/ m^3)	+5.69	+5.62	+6.08	+5.65	+6.49

*Units relative to national baseline = 1

Including these ventilation-related exposures leads to similar modest increases in the indoor winter temperatures as in the base case scenario. However, there is now an increase in mould levels in the housing stock since the reduced ventilation outweighs the increased temperatures. The increased airtightness protects against the ingress of external $PM_{2.5}$. However, our model suggests that this is outweighed by increased $PM_{2.5}$ from indoor sources (e.g. cooking) and there is thus an increase in average exposure overall. Similarly, exposures to ETS (in smoking households) and radon would be likely to increase.

Table 27 - Results of home energy efficiency intervention without (base case) and with inclusion of ventilation-related health impacts over 42 years

		All energy efficiency interventions					All energy efficiency interventions (with reduced ventilation)				
42 year time horizon (per household)		COPD	Heart disease	CMD	Age 65+	Low income	COPD	Heart disease	CMD	Age 65+	Low income
A	Number of people	2.20	1.53	1.09	1.49	1.81	2.55	1.80	1.47	1.74	2.52
B	Number of interventions	1.77	1.78	1.84	1.78	1.80	1.77	1.78	1.84	1.78	1.80
C	Change in energy demand (kWh/ yr)	-6,175	-6,398	-6,345	-6,890	-5,720	-6,910	-7,161	-7,178	-7,682	-6,463
D	Total QALYS/ 10^3	334.49	71.17	21.22	83.40	43.21	315.64	57.04	13.03	54.66	16.85
	Cardiovascular (incl MI + stroke)	33.52	21.45	4.78	39.37	16.09	22.05	15.95	1.56	30.83	8.11
	Common mental disorders	24.11	5.93	11.82	9.96	12.58	25.78	6.34	12.57	10.62	13.17
	COPD	275.99	43.72	4.41	33.95	14.07	291.12	46.10	4.74	35.80	14.73
	Asthma (children)	0.87	0.07	0.21	0.11	0.47	-1.17	-0.41	-1.10	-0.14	-1.60
	Cardiopulmonary	-	-	-	-	-	-16.66	-8.72	-3.27	-20.10	-13.49
	Lung cancer	-	-	-	-	-	-5.47	-2.21	-1.47	-2.35	-4.06
E	Intervention costs (£)	£11,566	£12,316	£12,608	£12,658	£12,055	£11,566	£12,316	£12,608	£12,658	£12,055
F	Change in energy costs (£)	-£9,217	-£9,881	-£9,259	-£10,588	-£8,787	-£10,418	-£11,135	-£10,563	-£11,899	-£10,059
G	Change in NHS health care costs (£)	-£236	-£114	-£24	-£196	-£81	-£57	-£26	£21	-£38	£57
	Incremental cost-effectiveness ratios (£/QALY)										
	NHS (G/ D)	-£706	-£1,608	-£1,149	-£2,355	-£1,868	-£180	-£458	£1,592	-£694	£3,360
	Government (incl NHS+LA) (E+G)/ D	£33,873	£171,452	£592,955	£149,417	£277,131	£36,463	£215,454	£969,315	£230,876	£718,808
	Householder (F/ D)	-£27,555	-£138,836	-£436,308	-£126,959	-£203,376	-£33,006	-£195,205	-£810,785	-£217,692	-£596,977
	Combined (E+F+G)/ D	£6,318	£32,616	£156,646	£22,458	£73,755	£3,457	£20,249	£158,530	£13,184	£121,831

The results demonstrate how important these ventilation-related outcomes may be (in particular over the longer term) for both health and the cost-effectiveness of energy efficiency measures. The incremental change in QALYs remains positive because of the large impacts on COPD due to increased temperatures. However, the exact relationship between changes in indoor temperature and COPD is highly uncertain (see 3.5 Interpretation of economic evidence). Without the large COPD impacts, the change in QALYs over the period would be likely to be negative. Even under the assumptions made here, for all target groups, the energy efficiency interventions becomes less cost-effective once ventilation-related changes are included.

Any change in ventilation is potentially important for health. However, the balance between potentially adverse and beneficial effects depends on the specific characteristics of the dwelling, its location, and its occupants. For illustrative purposes, we have considered here an extreme scenario in which no compensatory purpose-provided ventilation is installed in combination with the efficiency measures. Although unrealistic, it has been used here to demonstrate the principle and the potential issues. In reality, a level of additional ventilation is likely (though the exact level of compensation is uncertain).

Structural uncertainty 2: Duration of CMD impacts

The base case results demonstrated that, under the assumptions used, the morbidity impacts make up a substantial proportion of the total health impact. Here, an alternative assumption has been tested regarding the persistence of CMD impacts over time when interventions are targeted at those with CMD (that CMD impacts persist for the entire duration of the modelled time frame). The results confirm, as expected, that the interventions targeted at CMD would become more cost-effective if these impacts did not diminish over time (Table 28).

Table 28 – Results of interventions targeted at CMD under different assumptions regarding persistence of CMD impacts over 42 years

		Home energy efficiency		Fuel subsidy of £200		Home energy efficiency and fuel subsidy of £200	
	42 year time horizon (per household)	Base case CMD	Increased CMD	Base case CMD	Increased CMD	Base case CMD	Increased CMD
A	Number of people	1.09	1.09	1.01	1.01	1.05	1.05
B	Number of interventions	1.84	1.84	0.99	0.99	2.49	2.49
C	Change in energy demand (kWh/ yr)	-6,345	-6,345	708	708	-4,658	-4,658
D	Total QALYS/ 10^3	21.22	51.36	12.37	28.94	28.98	69.27
	Cardiovascular (incl. heart attack + stroke)	4.78	4.78	2.58	2.58	6.36	6.36
	Common mental disorders	11.82	41.95	6.50	23.07	15.80	56.08
	COPD	4.41	4.41	3.11	3.11	6.58	6.58
	Asthma (children)	0.21	0.21	0.17	0.17	0.25	0.25
E	Intervention costs (£)	£12,608	£12,608	£8,777	£8,777	£19,029	£19,029
F	Change in energy costs (£)	-£9,259	-£9,259	-£7,776	-£7,776	-£15,598	-£15,598
G	Change in NHS health care costs (£)	-£24	-£25	-£13	-£14	-£33	-£33
	Incremental cost-effectiveness ratios (£/QALY)						
	NHS (G/ D)	-£1,149	-£487	-£1,081	-£474	-£1,125	-£483
	Government (incl NHS+LA) (E+G)/ D	£592,955	£245,005	£708,765	£302,861	£655,412	£274,234
	Householder (F/ D)	-£436,308	-£180,289	-£628,833	-£268,716	-£538,142	-£225,176
	Combined (E+F+G)/ D	£156,646	£64,716	£79,931	£34,145	£117,270	£49,058

Structural uncertainty 3: Loss of life expectancy for cold-related deaths

Analysis of modelled changes in life expectancy under different assumptions about the concentration of CVD risk in the population was presented earlier in Table 16, demonstrating how concentrating CVD risk in an increasingly small population subgroup would reduce the life expectancy of those people, relative to average life expectancy. We tested the sensitivity of the base case results to different sizes of this ‘high risk’ group to cold-related cardiovascular death (Table 29 to Table 31). The overall QALYs appear to be relatively insensitive to these assumptions.

Table 29 – Results of interventions with 10% of population assumed to be at 'high risk' to cold-related cardiovascular death over 42 years

		All energy efficiency interventions					Fuel subsidy of £200				
42 year time horizon (per household)		COPD	Heart disease	CMD	Age 65+	Low income	COPD	Heart disease	CMD	Age 65+	Low income
A	Number of people	2.20	1.53	1.09	1.49	1.81	1.97	1.39	1.01	1.40	1.59
B	Number of interventions	1.77	1.78	1.84	1.78	1.80	1.00	1.00	0.99	1.00	0.99
C	Change in energy demand (kWh/ yr)	-6,175	-6,398	-6,345	-6,890	-5,720	784	866	708	936	556
D	Total QALYS/ 10^3	317.73	60.44	18.83	63.71	35.16	188.03	38.96	11.07	36.87	21.54
	Cardiovascular (incl MI + stroke)	16.76	10.73	2.39	19.69	8.04	9.73	5.77	1.29	10.23	4.43
	Common mental disorders	24.11	5.93	11.82	9.96	12.58	11.02	4.19	6.50	4.94	6.49
	COPD	275.99	43.72	4.41	33.95	14.07	166.74	28.95	3.11	21.67	10.30
	Asthma (children)	0.87	0.07	0.21	0.11	0.47	0.54	0.05	0.17	0.03	0.32
E	Intervention costs (£)	£11,566	£12,316	£12,608	£12,658	£12,055	£8,804	£8,807	£8,777	£8,806	£8,775
F	Change in energy costs (£)	-£9,217	-£9,881	-£9,259	-£10,588	-£8,787	-£7,687	-£7,556	-£7,776	-£7,447	-£7,976
G	Change in NHS health care costs (£)	-£156	-£63	-£13	-£103	-£42	-£92	-£36	-£7	-£55	-£24
	Incremental cost-effectiveness ratios (£/QALY)										
	NHS (G/ D)	-£491	-£1,047	-£686	-£1,616	-£1,207	-£491	-£912	-£649	-£1,480	-£1,116
	Government (incl NHS+LA) (E+G)/ D	£35,911	£202,723	£668,861	£197,049	£341,624	£46,333	£225,137	£792,051	£237,363	£406,239
	Householder (F/ D)	-£29,008	-£163,473	-£491,714	-£166,186	-£249,905	-£40,882	-£193,943	-£702,231	-£201,977	-£370,243
	Combined (E+F+G)/ D	£6,903	£39,251	£177,147	£30,864	£91,719	£5,451	£31,194	£89,820	£35,386	£35,996

Table 30 – Results of interventions with 5% of population assumed to be at 'high risk' to cold-related cardiovascular death over 42 years

		All energy efficiency interventions					Fuel subsidy of £200				
	42 year time horizon (per household)	COPD	Heart disease	CMD	Age 65+	Low income	COPD	Heart disease	CMD	Age 65+	Low income
A	Number of people	2.20	1.53	1.09	1.49	1.81	1.97	1.39	1.01	1.40	1.59
B	Number of interventions	1.77	1.78	1.84	1.78	1.80	1.00	1.00	0.99	1.00	0.99
C	Change in energy demand (kWh/ yr)	-6,175	-6,398	-6,345	-6,890	-5,720	784	866	708	936	556
D	Total QALYS/ 10^3	313.71	57.87	18.26	58.99	33.23	185.69	37.58	10.76	34.41	20.48
	Cardiovascular (incl MI + stroke)	12.74	8.15	1.82	14.96	6.11	7.39	4.38	0.98	7.77	3.37
	Common mental disorders	24.11	5.93	11.82	9.96	12.58	11.02	4.19	6.50	4.94	6.49
	COPD	275.99	43.72	4.41	33.95	14.07	166.74	28.95	3.11	21.67	10.30
	Asthma (children)	0.87	0.07	0.21	0.11	0.47	0.54	0.05	0.17	0.03	0.32
E	Intervention costs (£)	£11,566	£12,316	£12,608	£12,658	£12,055	£8,804	£8,807	£8,777	£8,806	£8,775
F	Change in energy costs (£)	-£9,217	-£9,881	-£9,259	-£10,588	-£8,787	-£7,687	-£7,556	-£7,776	-£7,447	-£7,976
G	Change in NHS health care costs (£)	-£137	-£51	-£10	-£81	-£33	-£81	-£29	-£6	-£43	-£19
	Incremental cost-effectiveness ratios (£/QALY)										
	NHS (G/ D)	-£436	-£881	-£557	-£1,365	-£1,000	-£437	-£770	-£529	-£1,247	-£927
	Government (incl NHS+LA) (E+G)/ D	£36,433	£211,953	£690,037	£213,212	£361,748	£46,975	£233,607	£815,017	£254,630	£427,575
	Householder (F/ D)	-£29,380	-£170,745	-£507,171	-£179,496	-£264,424	-£41,396	-£201,088	-£722,470	-£216,382	-£389,463
	Combined (E+F+G)/ D	£7,053	£41,209	£182,866	£33,716	£97,324	£5,579	£32,519	£92,547	£38,248	£38,111

Table 31 – Results of interventions with 1% of population assumed to be at 'high risk' to cold-related cardiovascular death over 42 years

		All energy efficiency interventions					Fuel subsidy of £200				
	42 year time horizon (per household)	COPD	Heart disease	CMD	Age 65+	Low income	COPD	Heart disease	CMD	Age 65+	Low income
A	Number of people	2.20	1.53	1.09	1.49	1.81	1.97	1.39	1.01	1.40	1.59
B	Number of interventions	1.77	1.78	1.84	1.78	1.80	1.00	1.00	0.99	1.00	0.99
C	Change in energy demand (kWh/ yr)	-6,175	-6,398	-6,345	-6,890	-5,720	784	866	708	936	556
D	Total QALYS/ 10^3	308.01	54.22	17.44	52.30	30.50	182.38	35.61	10.32	30.94	18.97
	Cardiovascular (incl MI + stroke)	7.04	4.50	1.00	8.27	3.38	4.09	2.42	0.54	4.30	1.86
	Common mental disorders	24.11	5.93	11.82	9.96	12.58	11.02	4.19	6.50	4.94	6.49
	COPD	275.99	43.72	4.41	33.95	14.07	166.74	28.95	3.11	21.67	10.30
	Asthma (children)	0.87	0.07	0.21	0.11	0.47	0.54	0.05	0.17	0.03	0.32
E	Intervention costs (£)	£11,566	£12,316	£12,608	£12,658	£12,055	£8,804	£8,807	£8,777	£8,806	£8,775
F	Change in energy costs (£)	-£9,217	-£9,881	-£9,259	-£10,588	-£8,787	-£7,687	-£7,556	-£7,776	-£7,447	-£7,976
G	Change in NHS health care costs (£)	-£110	-£34	-£6	-£49	-£20	-£65	-£20	-£4	-£26	-£12
	Incremental cost-effectiveness ratios (£/QALY)										
	NHS (G/ D)	-£356	-£619	-£360	-£932	-£663	-£359	-£550	-£348	-£854	-£623
	Government (incl NHS+LA) (E+G)/ D	£37,195	£226,529	£722,422	£241,108	£394,620	£47,914	£246,734	£849,913	£283,781	£461,894
	Householder (F/ D)	-£29,923	-£182,228	-£530,809	-£202,469	-£288,140	-£42,147	-£212,162	-£753,223	-£240,701	-£420,379
	Combined (E+F+G)/ D	£7,271	£44,301	£191,613	£38,639	£106,480	£5,767	£34,573	£96,690	£43,080	£41,514

3.2.2 Deterministic sensitivity analyses

In the following sensitivity analyses, we do not tabulate all combinations of interventions, target groups and time frames in each case but show illustrative examples to demonstrate the general patterns.

Deterministic sensitivity 1: Inclusion of solid wall insulation in home energy efficiency intervention

Since solid wall insulation is relatively more expensive than the other modelled energy efficiency measures, the base case energy efficiency intervention was repeated but with solid wall insulation omitted. The results suggest that the intervention would indeed become marginally more cost-effective without this measure (Table 32).

Table 32 – Base case home energy efficiency intervention results with and without inclusion of solid wall insulation over 42 years

		All energy efficiency interventions					Energy efficiency interventions excluding solid wall insulation				
	42 year time horizon (per household)	COPD	Heart disease	CMD	Age 65+	Low income	COPD	Heart disease	CMD	Age 65+	Low income
A	Number of people	2.20	1.53	1.09	1.49	1.81	2.27	1.46	1.09	1.46	1.74
B	Number of interventions	1.77	1.78	1.84	1.78	1.80	1.61	1.59	1.61	1.61	1.61
C	Change in energy demand (kWh/ yr)	-6,175	-6,398	-6,345	-6,890	-5,720	-4,968	-4,976	-4,775	-5,432	-4,455
D	Total QALYS/ 10^3	334.49	71.17	21.22	83.40	43.21	273.56	57.70	16.25	67.15	36.54
	Cardiovascular (incl MI + stroke)	33.52	21.45	4.78	39.37	16.09	27.28	16.77	3.73	31.20	13.15
	Common mental disorders	24.11	5.93	11.82	9.96	12.58	15.41	5.03	9.02	7.33	10.29
	COPD	275.99	43.72	4.41	33.95	14.07	229.95	35.82	3.34	28.50	12.64
	Asthma (children)	0.87	0.07	0.21	0.11	0.47	0.92	0.08	0.15	0.12	0.46
E	Intervention costs (£)	£11,566	£12,316	£12,608	£12,658	£12,055	£9,234	£9,628	£9,576	£10,029	£9,405
F	Change in energy costs (£)	-£9,217	-£9,881	-£9,259	-£10,588	-£8,787	-£7,341	-£7,403	-£6,915	-£8,156	-£6,689
G	Change in NHS health care costs (£)	-£236	-£114	-£24	-£196	-£81	-£193	-£90	-£19	-£156	-£66
	Incremental cost-effectiveness ratios (£/QALY)										
	NHS (G/ D)	-£706	-£1,608	-£1,149	-£2,355	-£1,868	-£707	-£1,558	-£1,168	-£2,324	-£1,814
	Government (incl NHS+LA) (E+G)/ D	£33,873	£171,452	£592,955	£149,417	£277,131	£33,048	£165,323	£588,044	£147,025	£255,556
	Householder (F/ D)	-£27,555	-£138,836	-£436,308	-£126,959	-£203,376	-£26,836	-£128,319	-£425,437	-£121,455	-£183,046
	Combined (E+F+G)/ D	£6,318	£32,616	£156,646	£22,458	£73,755	£6,211	£37,004	£162,607	£25,570	£72,511

Deterministic sensitivity 2: Baseline energy efficiency (low SAP)

The base case analysis was repeated but targeted only at energy inefficient dwellings, identified as being in the lowest quartile of SAP-rating. The results are presented in Table 33. In general, the modelled temperature increases achieved through energy efficiency interventions for the energy inefficient dwellings were greater than those for the general stock (not tabulated). As such, the interventions appear to be more cost-effective when targeted at low energy efficiency dwellings.

Table 33 – Base case results targeted at low energy efficiency dwellings (SAP < 30) over 42 years

		All energy efficiency interventions					Fuel subsidy of £200				
42 year time horizon (per household)		COPD	Heart disease	CMD	Age 65+	Low income	COPD	Heart disease	CMD	Age 65+	Low income
A	Number of people	1.81	1.42	1.38	1.39	1.61	1.70	1.19	1.18	1.29	1.30
B	Number of interventions	2.63	2.94	3.31	2.63	2.88	0.99	1.00	1.00	0.99	0.99
C	Change in energy demand (kWh/ yr)	-7,625	-9,843	-10,459	-10,049	-7,092	770	812	949	803	519
D	Total QALYS/ 10^3	603.38	139.59	64.27	154.53	102.28	174.05	33.23	13.08	31.72	18.29
	Cardiovascular (incl MI + stroke)	61.36	46.06	19.57	74.88	39.44	17.38	8.15	3.12	13.43	6.87
	Common mental disorders	23.30	0.00	43.09	29.07	51.57	4.63	0.00	9.08	3.55	8.03
	COPD	518.72	93.54	1.60	50.58	11.26	152.05	25.08	0.88	14.75	3.39
	Asthma (children)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
E	Intervention costs (£)	£20,553	£25,627	£24,133	£24,048	£22,347	£8,791	£8,807	£8,816	£8,792	£8,773
F	Change in energy costs (£)	-£18,074	-£24,280	-£18,847	-£23,483	-£18,011	-£7,328	-£7,194	-£7,274	-£7,152	-£7,749
G	Change in NHS health care costs (£)	-£436	-£245	-£96	-£370	-£192	-£125	-£46	-£15	-£68	-£34
	Incremental cost-effectiveness ratios (£/QALY)										
	NHS (G/ D)	-£722	-£1,756	-£1,488	-£2,396	-£1,877	-£717	-£1,376	-£1,179	-£2,137	-£1,844
	Government (incl NHS+LA) (E+G)/ D	£33,340	£181,824	£374,027	£153,227	£216,618	£49,792	£263,706	£672,637	£275,000	£477,924
	Householder (F/ D)	-£29,954	-£173,936	-£293,261	-£151,969	-£176,106	-£42,102	-£216,522	-£555,998	-£225,444	-£423,760
	Combined (E+F+G)/ D	£3,387	£7,888	£80,767	£1,258	£40,513	£7,690	£47,184	£116,639	£49,556	£54,163

Deterministic sensitivity 3: Level of subsidy in fuel subsidy intervention

The base case fuel subsidy intervention was repeated but with the amount of the subsidy decreased to £100 and increased to £200 (Table 34). The QALYs increased and decreased approximately in proportion to the amount of the subsidy and, hence, so did ICERs.

Table 34 – Base case fuel subsidy intervention results for £100 and £400 subsidies over 42 years

	42 year time horizon (per household)	Fuel subsidy of £100					Fuel subsidy of £400				
		COPD	Heart disease	CMD	Age 65+	Low income	COPD	Heart disease	CMD	Age 65+	Low income
A	Number of people	2.02	1.43	1.05	1.44	1.66	1.85	1.36	0.96	1.36	1.48
B	Number of interventions	1.00	1.00	0.99	1.00	0.99	1.00	1.00	0.99	1.00	0.99
C	Change in energy demand (kWh/ yr)	421	457	381	488	306	1,307	1,504	1,164	1,653	884
D	Total QALYS/ 10^3	111.56	25.31	6.99	25.98	15.29	303.05	69.32	18.93	74.57	36.39
	Cardiovascular (incl MI + stroke)	10.90	6.36	1.44	11.08	5.07	30.06	18.54	4.02	33.53	13.10
	Common mental disorders	6.28	2.40	3.71	2.68	3.85	17.14	6.42	9.71	8.06	9.06
	COPD	94.03	16.50	1.74	12.21	6.18	255.09	44.30	5.01	32.92	13.82
	Asthma (children)	0.35	0.05	0.11	0.01	0.18	0.76	0.05	0.19	0.06	0.40
E	Intervention costs (£)	£4,402	£4,403	£4,389	£4,403	£4,387	£17,608	£17,614	£17,555	£17,612	£17,550
F	Change in energy costs (£)	-£3,803	-£3,745	-£3,850	-£3,696	-£3,949	-£15,737	-£15,425	-£15,898	-£15,195	-£16,268
G	Change in NHS health care costs (£)	-£78	-£35	-£7	-£56	-£26	-£214	-£101	-£21	-£168	-£66
	Incremental cost-effectiveness ratios (£/QALY)										
	NHS (G/ D)	-£698	-£1,379	-£1,065	-£2,154	-£1,695	-£705	-£1,453	-£1,099	-£2,257	-£1,823
	Government (incl NHS+LA) (E+G)/ D	£38,761	£172,588	£626,627	£167,332	£285,313	£57,398	£252,637	£926,032	£233,914	£480,452
	Householder (F/ D)	-£34,089	-£147,943	-£550,666	-£142,274	-£258,331	-£51,928	-£222,524	-£839,645	-£203,756	-£447,060
	Combined (E+F+G)/ D	£4,671	£24,646	£75,961	£25,058	£26,982	£5,470	£30,113	£86,387	£30,158	£33,391

Deterministic sensitivity 4: Discount rate of 3.5%

The base case scenarios were repeated with the discount rate for all costs and QALYs increased from 1.5% to 3.5%. Cost-effectiveness is reduced considerably for the home energy efficiency intervention in this alternative scenario (Table 35). However, the fuel subsidy remains relatively unchanged despite the reduced intervention cost.

Table 35 – Base case results with discount rate increased to 3.5% for all costs and benefits over 42 years

		All energy efficiency interventions					Fuel subsidy of £200				
42 year time horizon (per household)		COPD	Heart disease	CMD	Age 65+	Low income	COPD	Heart disease	CMD	Age 65+	Low income
A	Number of people	2.20	1.53	1.09	1.49	1.81	1.97	1.39	1.01	1.40	1.59
B	Number of interventions	1.77	1.78	1.84	1.78	1.80	1.00	1.00	0.99	1.00	0.99
C	Change in energy demand (kWh/ yr)	-6,175	-6,398	-6,345	-6,890	-5,720	784	866	708	936	556
D	Total QALYS/ 10^3	238.99	51.03	15.22	60.32	30.64	141.46	32.10	8.88	34.11	18.43
	Cardiovascular (incl MI + stroke)	22.78	15.32	3.04	28.69	11.16	13.38	8.25	1.66	14.97	6.14
	Common mental disorders	17.32	4.26	8.86	7.16	9.04	7.91	3.01	4.87	3.55	4.66
	COPD	198.26	31.41	3.17	24.39	10.11	119.78	20.80	2.24	15.57	7.40
	Asthma (children)	0.62	0.05	0.15	0.08	0.34	0.38	0.04	0.12	0.02	0.23
E	Intervention costs (£)	£14,499	£15,491	£15,970	£15,936	£15,264	£6,248	£6,250	£6,230	£6,250	£6,228
F	Change in energy costs (£)	-£6,541	-£7,013	-£6,571	-£7,515	-£6,237	-£5,456	-£5,363	-£5,519	-£5,285	-£5,660
G	Change in NHS health care costs (£)	-£164	-£82	-£16	-£143	-£56	-£97	-£45	-£9	-£75	-£31
	Incremental cost-effectiveness ratios (£/QALY)										
	NHS (G/ D)	-£684	-£1,603	-£1,028	-£2,373	-£1,831	-£685	-£1,407	-£973	-£2,211	-£1,700
	Government (incl NHS+LA) (E+G)/ D	£59,981	£301,954	£1,048,328	£261,814	£496,273	£43,487	£193,320	£700,213	£181,018	£336,237
	Householder (F/ D)	-£27,370	-£137,413	-£431,802	-£124,579	-£203,513	-£38,566	-£167,069	-£621,162	-£154,948	-£307,149
	Combined (E+F+G)/ D	£32,611	£164,540	£616,526	£137,235	£292,760	£4,921	£26,250	£79,051	£26,070	£29,088

3.2.3 Probabilistic sensitivity analysis

The results of the probabilistic sensitivity analyses are presented below. The analyses focused on a single target group, chosen to be households with occupants aged >64 years. The interventions examined include all major energy efficiency retrofits (loft and wall insulation, double glazing upgrade, condensing boiler and gas central heating installation), where eligible.

In each analysis, two plots are shown. The first shows the scatter plot of the incremental costs and incremental benefits in the cost-effectiveness plane. The second plot shows the cost-effectiveness acceptability curve (CEAC) which is the probability that the intervention is cost-effective at different willingness to pay thresholds. In general, one expects the boundary of the scatter plots to be ellipsoidal and the axes of the ellipse not to be perpendicular to the axes of the cost-effectiveness plane. However, in situations where the uncertainty in the parameters in the Monte Carlo simulations are represented by symmetrical distributions (such as normal and uniform distributions) and the cost and cost-effectiveness calculations are approximately linear in the range analysed, the boundaries of the scatter plots tend to be nearly circular.

NHS perspective

Here, there are no interventions costs, only reduced health care costs, so ICERs are all negative. Figure 5 shows the results of the simulation and the willingness to pay and its probability of being cost effective as both 1 (i.e. always being cost effective as the costs are negative).

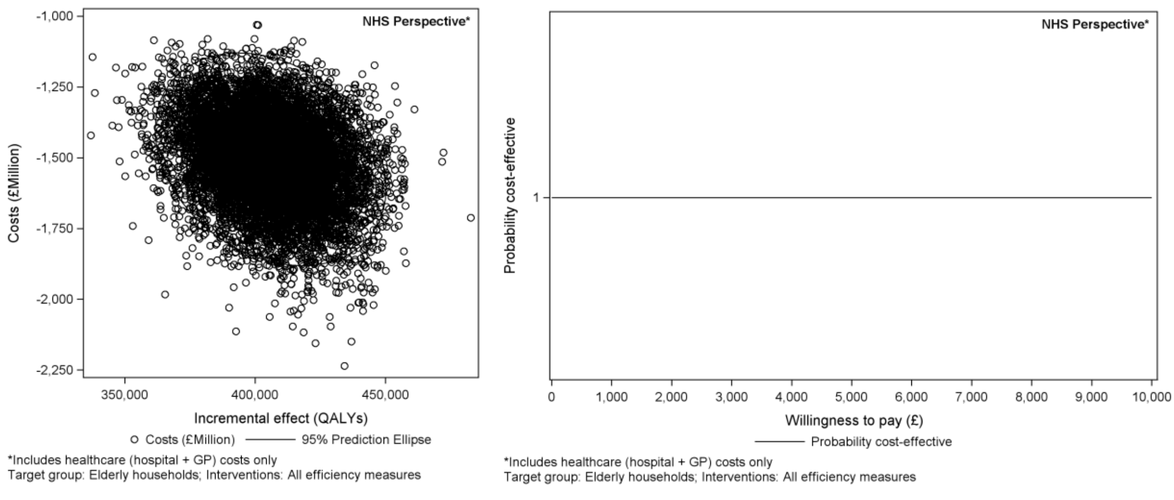

Figure 5 – Incremental cost-effectiveness scatterplots and cost-effectiveness acceptability curves for NHS perspective

Government (including NHS and local authorities) perspective

Figure 6 shows that a willingness to pay of £150,000 offers a 50% probability of being cost-effective, with a tight range of +/- £15,000 within 5% and 95% probability of being cost-effective. In this situation, the costs are assumed to accrue to the NHS and local authorities.

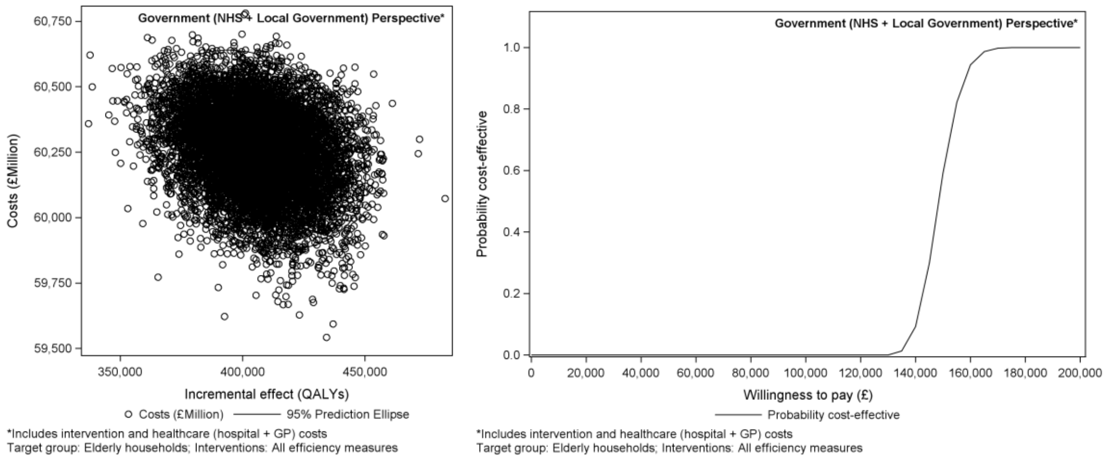

Figure 6 - Incremental cost-effectiveness scatterplots and cost-effectiveness acceptability curves for Government (including NHS and local authorities) perspective

Householder perspective

In this situation, costs are assumed to accrue to the householder in terms of energy savings but there is no associated intervention cost, since the householder receives a complete subsidy for the cost of the intervention. The cost-effectiveness ratio is negative and the acceptability curve is always equal to 1 (Figure 7).

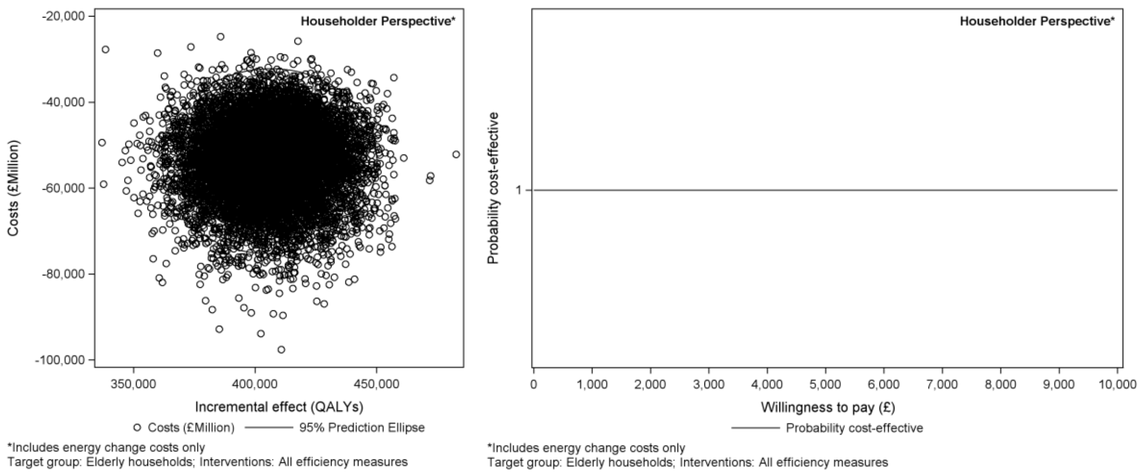

Figure 7 - Incremental cost-effectiveness scatterplots and cost-effectiveness acceptability curves for Householder perspective

Combined (Government + householder) perspective

Figure 8 shows that a willingness to pay of £15,000 offers a 50% probability of being cost-effective, with a tight range of +/- £15,000 within 5% and 95% probability of being cost-effective. In this situation, the intervention costs are assumed to accrue to a number of different parties (including local government) and NHS cost savings and household energy savings are also included.

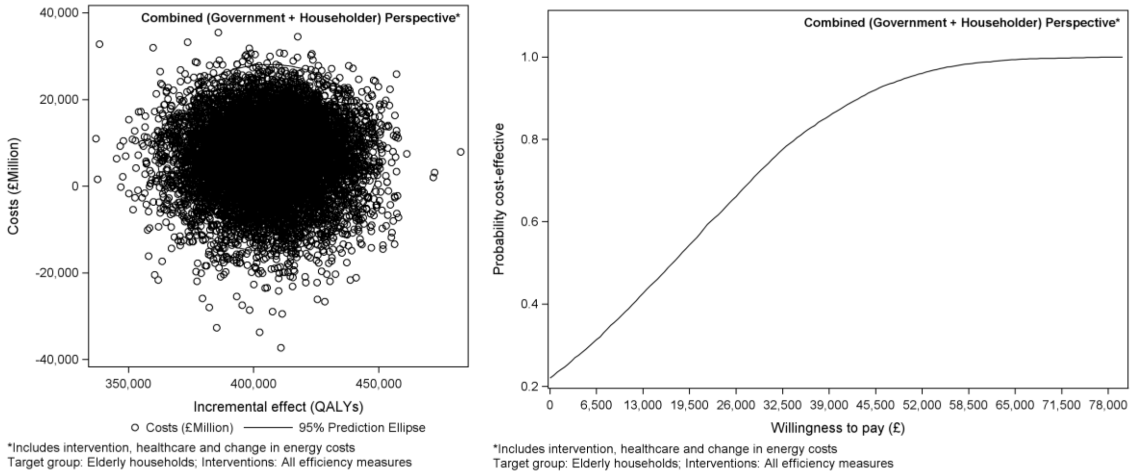

Figure 8 - Incremental cost-effectiveness scatterplots and cost-effectiveness acceptability curves for Combined (Government + householder) perspective

3.3 Validation

The outputs of the economic model have been validated in various ways. The modelled estimates for the base case energy performance were compared against observed national and sample stock distributions to check the accuracy of the model outputs, see Table 36 (Hong et al., 2006, 2004; Oreszczyn et al., 2006a, 2006b; Stephen, 1998). The modelled average dwelling fabric heat loss is 274 W/K and is greater than both Warm Front and national modelled estimates, 18% and 25% respectively (DECC, 2012b; Hong et al., 2006). The modelled average heat system efficiency is 76% compared to national estimates of 74% (Utley and Shorrock, 2008).

The modelled average English dwelling permeability is 14 $m^3 m^{-2} hr^{-1}$ compared to 17 $m^3 m^{-2} hr^{-1}$ in Warm Front and 14 $m^3 m^{-2} hr^{-1}$ from an observed national survey (Hong et al., 2004; Stephen, 1998). The modelled English dwelling exposure concentrations (ETS, $PM_{2.5}$, radon, temperature and mould) were compared with relevant observed surveys and found to be very close or within a range in all cases but mould, see Table 37 (Dimitroulopoulou et al., 2006; Gray et al., 2009; Hänninen et al., 2004; ONS, 2008; OPDM, 1998; Oreszczyn et al., 2006a, 2006b; Shrubsole et al., 2012).

Table 36 - Comparison of modelled English housing stock building performance and values from Warm Front and national estimates (DECC) and surveys (Stephen, 2000)

	Modelled	Warm Front[a]		National	
Building Performance	Mean	Mean	Source	Mean	Source
Fabric heat loss (W/K)	274	224	Oreszczyn et al. 2006	203.8	DECC, 2012
Heat system efficiency (%)	76%	67%	Hong et al. 2009	74%	DECC, 2008
Permeability ($m^3m^{-2}hr^{-1}$)	13.8	17.2	Hong et al. 2006	13.9	Stephen, 2000

Note: [a]Warm Front Study

Table 37 - Comparison of modelled English housing stock exposure concentrations and observed survey or estimates of concentrations in houses

Exposures	Modelled	Comparison	Source
Temperature - living room (°C)	18.6	17.9 - 19.1	Hong et al. 2006, OPDM 1998

Temperature - bedroom (°C)	17.1	15.9 - 18.5	Hong et al. 2006, OPDM 1998
Indoor $PM_{2.5}^{a}$ (μg/ m^2)	17	17 - 25	Hanninan et al. 2004, Dimitroupolou et al. 2006
Indoor $PM_{2.5}^{b}$	10.9	9.3*	Shrubsole et al. 2012
Outdoor $PM_{2.5}$	6.1	6.1*	Shrubsole et al. 2012
Radon (Bq/ m^3)	26.2	21	Gray et al. 2009
Mould (% with MSI >1)	11.5	14.6 - 21.2	OPDM 1998, Oreszczyn et al. 2006
% of homes with smoker	21.2	21	ONS 2008

Note: a) Weighted average values of kitchen (10%), lounge (45%) and bedroom (45%); b) Indoor sources of $PM_{2.5}$ relate to cooking only with an emission rate of 1.6 μg/ min; * Indicates modelled estimate.

The exposure pollutant model CONTAM has been validated throughout its development (Emmerich, 2001) for use in multi-zonal airflow and contaminant modelling. The stock-level exposures derived by the model are validated where possible against measurements of exposures in the English stock. The distribution of radon exposures is scaled by adjusting the proportion of the stock in regions with low, medium, and high radon emission rates to match the distribution evaluated by (Gray et al., 2009). The proportion of the modelled stock with a mould severity index greater than 1 is similar to that measured in dwellings as part of the Warm Front Study (Oreszczyn et al., 2006b) and the modelled stock-level $PM_{2.5}$ concentration is in broad agreement with measured values (Hänninen et al., 2004).

3.4 Interpretation of economic evidence, including subgroup analysis

The modelling of the health impact of home energy efficiency measures and their economic assessment relies on a chain of models each of which has multiple assumptions and sources of uncertainty. Results should therefore be interpreted as indicative only and in most cases are more interpretable with respect to the relative patterns of change than for the absolute estimates of impact and cost.

3.4.1 Home energy efficiency

The key results of the home energy efficiency intervention are as follows:

(1) With regard to targeting, households containing at least one person with COPD or at least one person with heart disease represent fairly small target populations (1 million and 1.8 million dwellings, respectively), while households containing someone with CMD represent around 3.6 million homes. Households containing at least one person aged 65 years or more and those in the bottom quintile of the household income distribution represent appreciably larger target groups (4.9 and 3.4 million dwellings, respectively). It is worth noting that these target groups are not fixed in relation to the dwelling. People moving home, the aging of families within a given home, and changes in health status over time mean that interventions targeted at dwellings occupied by a household with relevant characteristics over time will become mismatched to the original target. Our modelling does not explicitly allow for the effect of people moving home. The targeting of homes occupied by someone with CMD is likely to be especially problematic, as the nature of CMD means that the affected population will change over time. Moreover, it is probably hardest to identify homes occupied by someone with CMD, especially given the fluctuating nature of the disorder.

(2) The cost of interventions, if applied to all dwellings in the target groups, would represent very large investments nationally, ranging from around £1.4 billion for the upgrades of all homes occupied by at least one person with COPD, to almost £7.3 billion for all homes containing at least one person currently aged 65 years or more.

(3) The specification here was the installation of all home energy efficiency measures in eligible homes, meaning that all possible upgrades (loft insulation, double glazing, etc.) were carried out in target dwellings where the English Housing Survey indicated there was potential to do so. Despite this, the model estimates of the increase in the standardized indoor temperature (SIT) were fairly modest, ranging from 0.33 °C (for homes in the bottom quintile of the income distribution) to 0.39 °C for homes occupied by at least one household member aged 65 years or more. These modest rises are predicted from the empirical relationship between SIT and whole dwelling E-value, which suggests that at energy efficiency levels better than (i.e. below) around 300 W/K, further improvement in energy efficiency does not result in an increase in SIT. In the 2010 EHS, we estimate that around 44% of dwellings are already at this 'plateau' and for them no increase in temperature is estimated with additional energy efficiency measures. For other households individual energy efficiency measures have relatively small impact on the SIT (fractions of a degree Celsius), and few homes are deficient in multiple aspects of energy efficiency. The net result is a limited impact on temperature increases (and proportionately also on the mould index) with correspondingly modest impact on most health outcomes. From an equity point of view, it is interesting to note that the smallest temperature rises are predicted for homes on low income.

(4) The distribution of impacts on health show that the largest gains are for COPD and heart disease, with generally smaller impacts on CMD and smallest of all on childhood asthma. Although CMD has a high prevalence, the modest impact in the scenarios reflects a fairly high utility weighting (i.e. small deficit) and our assumptions to reflect the fact that CMD is not usually a lifelong condition. The changing pattern of illness over time (coupled with the unmodelled effect of people changing homes) means that the protective benefit of energy efficiency should be lower, at least in the scenario which specifically targets people with CMD. The small impact on childhood asthma largely reflects that all of the target populations, with the exception of low income households, are relatively old, and few of their households contain young children. We also assume that any adverse effect on childhood asthma reduces to zero above age 16 years.

(5) Because the health impacts in these scenarios (where no ventilation change is assumed) are all beneficial, the net change in healthcare costs, covering GP consultations and hospital admissions, is also negative (i.e. cost saving). The health care cost saving per dwelling or person is smallest for the scenario that targets people with CMD, and relatively larger for those with COPD, or heart disease or persons aged 65+ years. They are relatively more modest for households in the bottom quintile of household income.

3.4.2 Fuel subsidy

The key results of the fuel subsidy intervention are as follows:

(6) The results for the £200 fuel price subsidy broadly mirror those for energy efficiency investments in relative terms, as the target groups are the same, but the temperature

impacts are more modest (ranging from 0.13 °C for low income households, to 0.24 °C for households containing at least one member aged 65 years or more). These changes are less than those seen with the energy efficiency investments, with correspondingly small impacts on health. They would of course be greater with a larger subsidy.

(7) The scenario we tested with a subsidy of £200 is an arbitrary figure, but the same as that currently paid under the UK government's Winter Fuel Payment scheme for someone born on or before 5 January 1952 living on their own. This would buy the equivalent of around 4000 kw.hr of heating energy at £0.05 per unit *if* all were spent in improving indoor heating. The improvements in temperature and health benefit cannot be directly scaled by the level of subsidy, as temperature rises will be limited by the plateau effect at around 18.4 °C. However, as a first approximation, doubling the subsidy nearly doubles the health benefit, in particular for the least energy efficiency dwellings (Table 34).

3.4.3 Cost-effectiveness

Summary estimates of input and output costs *per household* and the associated cost-effectiveness ratios from different perspectives for the base case analysis are summarized in Table 24 and Table 25. Again, it is import to emphasize that these entail large uncertainties, and should be interpreted as indicative only. Note also that the main results based on temperature change alone do not include any effects of ventilation change, which may have substantial impact even if the intention is to provide sufficient purpose-provided ventilation (trickle vents and the like) to ensure no overall change (see sensitivity analyses). Moreover, no allowance has been made for the frequency with which people move home, which will further downgrade the relative benefits of interventions targeted at specific population groups.

With regard to targeting, interventions aimed at adults with COPD appear to have the greatest impact. However, these results are highly dependent on the assumed risk reduction of COPD morbidity with a warmer home. We found it difficult to identify a robust estimate of such risk reduction. Intervention based studies in the UK (Osman et al., 2008) provide no clear evidence of benefit, but evidence from New Zealand (Howden-Chapman et al., 2007) in particular suggests relatively large impacts, though New Zealand housing is appreciably different from that in the UK. Our central estimate of a relative risk of 0.9 for a one °C increase in SIT represents a compromise between limited UK evidence and less relevant (to England) New Zealand data. The COPD results should be treated very cautiously, and may not be nearly as favourable as the tabulated figures suggest.

Interventions aimed at people with CMD are relatively modest despite the high prevalence of CMD. This is partly explained by the small quality of life impact and partly by our assumption of a high recovery rate in what is a naturally fluctuating disease which is often responsive to treatment over months. The literature suggests that the majority of people with clinical symptoms of depression, for example, recover within 12 months or so, but may suffer recurrent bouts with a median of around four or five episodes over a lifetime (Richards, 2011). To allow for this, we assumed that the prevalence of CMD in those initially targeted because they had CMD would fall to 50% after one year and 25% after two years, and then remain at this underlying level. These are not precise estimates, but they are designed to lead to a high average prevalence rate among this targeted population, and to reflect the fact that the benefits to symptom reduction will be reduced because of the fluctuating nature of the disease. The impact of targeting households on the basis of someone with CMD symptoms is correspondingly reduced, therefore. However, this argument does not apply to other population samples because, on average, those who recover from mental illness will be balanced by others who develop it. There is an argument that all households benefit because of improvements in mental well-being short of changes to recognized clinical symptoms (e.g. simple thermal comfort), but the quantification is based on estimates of changes to mild clinical disease.

The benefits of interventions targeted at the households containing someone aged 65 years or more seem generally larger than interventions targeted at the bottom quintile of income. This in part reflects the higher underlying rates of relevant clinical conditions at older ages, together with slightly greater temperature changes.

The total costs of intervention are broadly similar for all energy efficiency interventions (including solid wall insulation) and fuel subsidy at £200 per household a year. (Note that the fuel subsidy is assumed to increase in proportion to fuel price inflation over time, which means the total cost over five years is greater than £1000, for example.) However, it is important to note that the costs of energy efficiency intervention are based on the accumulation of annualized costs over the relevant time horizon. Unless there is a suitable financing option, the reality is that householders or other funders would have to cover the whole capital cost at the outset (recall that our scenarios assume immediate implementation at time zero), and if the household moves away or household members die before the end of the assessment time horizon, the ratios of costs to benefits for them will be correspondingly poorer.

Energy efficiency interventions reduce energy costs (and unquantified CO_2 emissions), but fuel subsidies increase them, though by less than the cost of the subsidy. The appreciable energy savings with energy efficiency interventions make a substantial contribution to improving cost effectiveness ratios.

Finally, the sensitivity analyses suggested that the interventions are likely to become more cost-effective when targeted at homes in the stock with poor energy efficiency (low SAP) and (to a lesser extent) when solid wall insulation is not included as part of energy efficiency upgrades.

Incremental cost-effectiveness ratios

Incremental cost-effectiveness ratios are generally better over 5 year time horizons than over 42 year time horizons for interventions targeted at households containing one or more member with a target disease (COPD, CMD, heart disease). Again, this is primarily due to the fact that in this work intervention costs have been annualised. Clearly if energy efficiency installation costs were experienced 'up front', this would make such interventions expensive in the short-term. However, it also in part reflects the fact that the number of people with those target diseases at the outset declines over time as people die or recover (again we don't allow for moving home). For households containing someone aged 65 years or more, the cost-effectiveness ratios are generally better over the longer time horizon, which may in part reflect an effect of further ageing over time, with corresponding increases in underlying population mortality rates. The pattern for low income households is not consistently better or worse with the longer time horizon.

If the NHS does not contribute to the cost of intervention, the cost-effectiveness ratios from an NHS perspective are all negative, as the NHS is a beneficiary from reduced health care costs. If the Government (including NHS and/ or local authorities) do contribute to the intervention costs, the cost-effectiveness ratios ((intervention + health care costs)/ QALYs) are relatively high for all forms of interventions and targeting, with the exception of the highly uncertain COPD target group.

The results for the householder perspective (assuming here that individual householders are not paying for energy efficiency interventions) demonstrate the large additional benefits gained by reduced fuel bills. In the case of energy efficiency, the interventions reduce energy use and the resulting energy cost savings largely offset the intervention costs. For fuel subsidy, although more energy is used overall, there is a net energy cost saving due to the £200 payment. The ratios seem not so favourable for energy efficiency interventions targeted at CMD (largely because of the assumed recovery rate in clinical disease) or at low income households in general.

Overall, the fuel subsidy, at the starting level of £200 per household per year, gives slightly smaller temperature-related impacts than energy efficiency interventions because of the smaller associated average temperature improvement. Without the saving in energy use, the cost-effectiveness ratios for fuel subsidy are poorer than for energy efficiency interventions, and generally are not favourable in absolute terms with the possible exception of the scenario targeted at households containing at least one person with COPD. It can be concluded that energy efficiency intervention is generally better than fuel subsidy if the costs of the intervention and energy use are counted. However, in circumstances where a householder has comparatively short life expectancy or expects to move home soon, fuel subsidy may be a preferable option than the investment of the capital costs for that household (though subsequent inhabitants would benefit from any energy efficiency intervention).

3.5 Limitations

As with all models, the economic modelling entails multiple assumptions and uncertainties related to both the input parameters and the quantified estimates. Whilst great effort has been employed to test the model, given its complexity, some limitations around uncertainty remain.

3.5.1 Overview of limitations

There are uncertainties related to the data inputs and model estimates. The underlying data used in the model is based on the EHS, which is statistically representative of the English housing stock. The conversion process of the EHS into an input buildings physics dataset includes a number of assumptions that increase the uncertainty of the modelling. It is not possible to provide a detailed survey of all aspects of such uncertainty, but the table below lists each of the key components that feed in to the impact calculation and summarizes, using a simple scoring system, the level of certainty associated with each, with a brief explanation (Table 38).

Table 38 – Summary of key limitations

Area of estimation	Parameter	Certainty in response or relationship	Comment
Population data	Sample representativeness	+++	Data are based on dwellings and their inhabitants in the English Housing Survey.
Building characteristics	Changes in building performance	++	Reasonably good for thermal characteristics, but the relationship between energy efficiency interventions and permeability/ ventilation characteristics is from assumed functions based on expert judgement and empirical data (Hong et al., 2004).
Changes in environmental	Temperature	+	Thermal characteristics modelled from specified changes to building fabric. However, there is

exposures			uncertainty over the impact of such changes on indoor temperatures because of behavioural factors/ choice (e.g. the degree to which householders take improved energy efficiency as warmer temperatures rather than lower fuel bills – the 'take back' factor) and the capacity and operation of the heating system. Mainly based on an empirical function derived from the *Warm Front* study (Oreszczyn et al., 2006a).
	Indoor air quality	++	Based on complex models that involve a range of assumptions. Such assumptions include those relating to changes in dwelling permeability and ventilation systems and hence air exchange that can be affected by behaviour. For example, these have been explored for $PM_{2.5}$ (Shrubsole et al., 2012)
Exposure-health impact relationships	Cold: mortality	+	There is limited evidence relating health to measured indoor temperatures. Evidence used mainly based on one English study of the degree to which housing modifies the outdoor temperature-mortality relationship (Wilkinson et al., 2001).
	Cold: COPD	+/ -	There is limited evidence relating COPD and exacerbation of COPD symptoms to indoor temperatures. There are large variations in reported exposure-response coefficients from different studies and locations. At present, the evidence is uncertain and caution is required in its interpretation.
	Cold: mental health	+	There is direct evidence for the impact of cold on thermal comfort (Green and Gilbertson, 2008), but mixed evidence on overall mental well-being (Liddell and Morris, 2010; Thomson et al., 2013), although suggestive of adverse impact. Duration of adverse impact unclear, however. For the purposes of evaluation, the model provides options for varying the assumption about the persistence (time decay) of the adverse mental health impacts, which can have appreciable bearing on the impact calculation.
	$PM_{2.5\ (outdoor)}$	+++	Strong epidemiological base for adverse effects of PM, but nearly all based on studies of outdoor pollution (Pope et al., 2004, 2002).
	$PM_{2.5(indoor)}$	+	There is uncertainty about the relative toxicity of particles generated from indoor sources compared with those from outdoor sources. They might be as toxic or even more toxic as PM derived from outdoor sources, but the single + rating indicates the lack of clarity (Pope et al., 2004, 2002).
	Radon	+++	Strong epidemiological evidence for adverse health effects of indoor radon. Long time lag assumed for development of disease from increased exposure and for decay of risk with reduction in exposure (Darby et al., 2005).
	Second hand tobacco smoke	++	Reasonably clear epidemiological evidence for the selected health outcomes included in the model (including from meta-analysis) (Law et al., 1997; Lee and Forey, 2006).
	Mould	++	Repeated reports of link between mould and respiratory and general health problems (Fisk et al., 2007; Howden-Chapman et al., 2007), especially in children (Howden-Chapman et al., 2007), but interpretation remains unclear because of uncertainty over influence of confounding factors and causality. A major uncertainty is what duration of effect there might be on respiratory/ asthmatic symptoms in children.
Health impacts	Method of calculating changes in years of life and quality adjusted life years	++	Based on established life table methods with assumed lag functions for the development of new risks and the decay of reduced risks. It is important to note that the calculations of change in years of life are 'artificial constructs' that entail a number of assumptions about expected future health experience over a long time course (50+ years). Calculations of COPD, mental health and asthma

		impacts are based on direct application of relative risks to study- or survey-based data on disease prevalence.
Health state utility values	+	Values assumed to represent average disease conditions. Based on values used in previous NICE documents. However, studies show a wide range of estimates depending on, for example, age and disease severity.

KEY
+/ - Equivocal
\+ Weak evidence/ certainty
++ Moderate evidence/ certainty
+++ Strong evidence/ certainty

3.5.2 Key limitations of the building model

The key limitations of the building model include:

Energy performance of buildings

Structural uncertainties relate to the model specification. Of most relevance to the economic modelling is the population sample used as inputs, the characterisation of the environmental conditions within the residential building stock and assumptions around the fuel subsidy relationship.

The conversion of the English Housing Data relies on methods outlined in (DECC et al., 2012) and uses values drawn from the reduced Standard Assessment Procedure (RdSAP) method. Each dwelling component (e.g. wall, window, roof) is matched against measured values for heat loss values (i.e. u-values), the heat system seasonal efficiency, and the number of air-changes associated with infiltration across the fabric. These values are not altered within the model.

Further, the method for estimating the energy demand relies on the method set out in (Hamilton et al., 2011), which uses a standard method of heating degree days to determine the heat demand below a given internal temperature that excludes solar and internal gains. It is assumed that all dwellings have an average internal gain of 3.2 °C, following (Day et al., 2003).

Pollutant exposure model matching

The variation in the geometries of the EHS dwellings is assumed to be adequately represented by 10 archetypes. The matching of these archetypes to the EHS dwellings relies on matching rules that use survey dwelling features from the EHS. The matching process included using a set of rules to determine which archetype is a suitable match in terms of its physical parameters and ventilation characteristics.

The first rule applied to the EHS stock was to select an archetype that matches the surveyed dwelling type (i.e. flats, terraced houses, bungalows and detached houses). This ensured that the geometric form modelled in the building model broadly represented a given dwelling. The second rule used gross floor area to match archetypes with multiple dwelling types (i.e. terraced houses), for example the larger dwellings were matched into the larger archetypes of the dwelling forms. Matching by size and type will have an impact on the absolute levels of pollutants experienced within a dwelling.

Matching for flats was further subdivided into three groups: below first floor, first floor, and above first floor, in order to allocate the correct radon concentration levels. The division allowed for flats on the ground and below to receive the full concentration of radon (weighted for the stock), those on the first floor receive 50% of the ground floor exposure, and those above the first floor and above had no exposure to radon.

All dwellings built after 1990 and a random sample of 8% of dwellings before 1990 are assumed to have trickle vents. A difference in the distribution of trickle vents across the English housing stock will affect the exposures experiences by occupants to the various pollutants.

Occupant behaviour in the building models

The building models of ventilation and pollutant concentrations require assumptions to be made about the behaviour of occupants, with regards to their interaction with windows, production of pollutants, and the removal of pollutants. For example, windows can be opened when indoor temperatures become high to either enable cooler air from outdoors to ingress, or to allow the cooling effects of cross-ventilation. Uncertainty around the production of pollutants could relate to cooking (which produces particulate matter and moisture) and bathing (which produces moisture) patterns. Occupants themselves also produce moisture and therefore production rates in each room of the dwelling is related to the movement of the occupants. Occupants can also actively remove pollutants through the use of extract fans and windows during cooking times.

Larger dwellings are assumed to have more occupants and therefore more instances of window opening and use of the bathroom. However no variation is assumed across the housing stock for dwellings of the same number of occupants, therefore potentially underestimating the spread in air change rates and pollutant concentrations in the EHS dwellings.

3.5.3 Key limitations of the health model

The key limitations of the health model include:

- The primary health impact calculations in the model are performed using commonly used life table methods. However, for each modelled health outcome, the baseline mortality risks used in these life table were based on population average mortality rates which varied only by age and sex, taking no account of other factors which may affect underlying health (i.e. assuming average life expectancy according to age and sex). However, we did reduce life expectancy for those identified as suffering from COPD and heart disease in line with published estimates of life shortening associated with those conditions.

- The morbidity estimates presented here make the assumption that there is a constant relationship between the burdens of mortality and morbidity for each outcome. Clearly this is relatively crude but is likely to be reasonable at the population level. Similarly, the NHS health care costs have been estimated using the assumption that changes in health outcomes will lead to proportional changes in health care contacts. In particular, assuming a proportional change in total GP consultations which is driven by the total change in hospital admissions is likely to underestimate GP consultations for conditions which do not require regular hospitalisation.

- The morbidity impacts on COPD, CMD and asthma assume that changes to SIT and mould affect the prevalence of these conditions but the model does not account for improvement (or worsening) of symptoms and associated changes to the applied utility weights. It also does not account for variations in utility weights by age.

- As described previously, the model results presented in this report make no allowance for the potential effect of people moving home. In reality, such movements would tend over time to reduce the match between houses with the energy efficiency intervention and the population originally targeted by the intervention because each year a proportion of the target group will move out of their original homes and others (most of whom are not part of the original target group) will move into them. To illustrate, we estimate below the effect of such movement on the proportion of the original COPD target group remaining in intervention dwellings as a function of time after intervention. The estimates are made using four simplifying assumptions:

1. There is no correlation between target group and the probability of moving home (which is therefore assumed to be the same as that in the population as a whole);
2. The probability of moving in future years is not affected by moving in previous years;
3. The number of dwellings with the original energy efficiency intervention remains fixed and does not change by year;
4. No new cases of COPD are added to those in the original target population.

The starting proportion of people with COPD (the original target group) is 0.0582 (5.82%) and the probability of moving home in any one year is 0.11 (11%). This value for the UK was estimated using data from the Office for National statistics (http://www.ons.gov.uk/ons/rel/social-trends-rd/social-trends/social-trends-41/index.html). We estimated the proportion of the original target group remaining in the original intervention homes in year i to be:

- the proportion of COPD patients in intervention homes in year i-1 reduced by the fraction (0.11x(1-0.0582))

  plus

- the proportion of COPD patients in non-intervention homes in year i-1 multiplied by (0.11x(1-0.0582))

The second quantity reflects the small proportion of the original target group that moves back into intervention homes after having moved out from non-intervention homes. Figure 9 below indicates the evolution over time of the proportion of the COPD group in the original intervention homes and the proportion of the target COPD group in non-intervention homes by year. As can be seen, the proportion of the original target group remaining in the intervention homes declines exponentially such that the proportion is reduced by around 35% by five years after intervention and by 93% after 42 years. The time averaged proportions over 5 years and 42 years are, respectively, 23% and 74% - which therefore indicate the expected dilution of the targeted benefits over these periods of follow up.

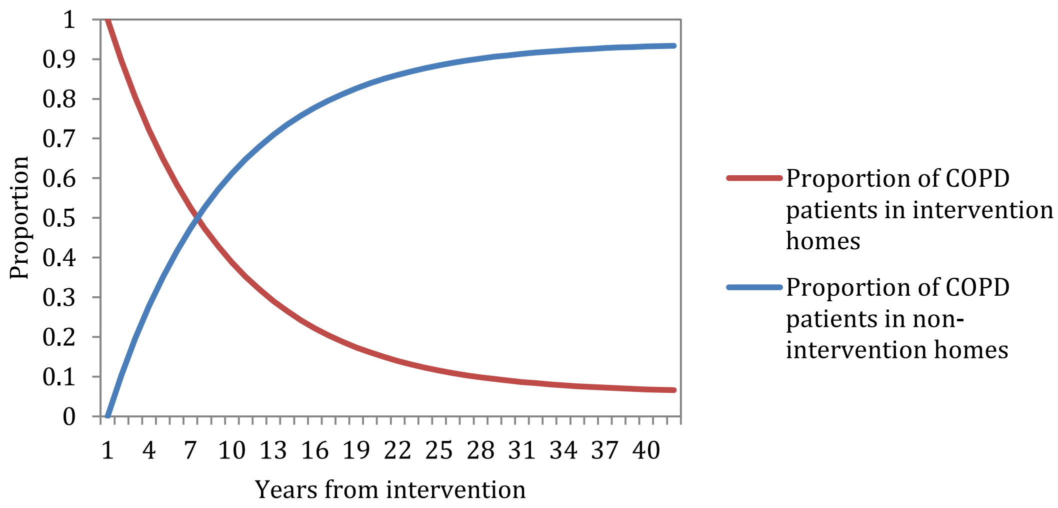

Figure 9 - The effect of moving home on the proportion of patients with COPD remaining in (original) intervention homes as a function of years since the intervention

In reality, the COPD target group are probably less likely to move than others, especially if their homes have just been retrofitted. If we assume the fraction that move home each year to be as low as 5%, the dilution would be around 14% over five years and 56% over 42 years.

- Limitations of the epidemiological relationships for the environmental exposures considered in the model have been described in Table 38 above. Given their centrality to the model and the research questions of this work, the most important of these limitations are the large uncertainties associated with cold-related health impacts on cardiovascular mortality, CMD, and (particularly) COPD. These limitations are discussed elsewhere in this report (e.g. see Table 38 and section 3.4).

4 Conclusions

- The effect of home energy efficiency investments is fairly modest in terms of temperature increases, and those relating to fuel subsidy at an initial value of £200 per household per year are on average smaller still.
- For most outcomes, our results suggest that home energy efficiency interventions are probably not cost effective (i.e. ICERs > £30k/ QALY) if the benefits are counted in health terms alone.
- Home energy efficiency interventions are energy saving and the associated energy cost savings in part offset the capital investment cost. If such savings are included in the cost-effectiveness ratios, the net ICERs are more favourable.
- In calculations that include energy as well as intervention costs, the overall ICERs appear relatively favourable for interventions aimed at households containing someone with COPD, heart disease or age 65 years or more. The ratios do not appear to be as beneficial for households targeted on the basis of CMD or low income alone.
- Cost-effectiveness ratios are slightly more favourable over a 5 year than a 42 year time horizon where people with specific diseases are targeted, in part because the number of disease-specific beneficiaries declines over time through death or recovery.
- Fuel subsidies increase fuel use. Fuel subsidy is less cost-effective than home energy efficiency, but it may be a more suitable option over shorter time frames to avoid the large capital investment costs for individuals with comparatively short life expectancy or if they expect to move home in a comparatively short period.
- Targeting interventions at people with CMD appears to have a less favourable cost-effectiveness ratio than interventions aimed at other disease groups if an assumption is made of appreciable recovery from CMD, which is a disease with a fluctuating natural history.
- Cost-effectiveness ratios are improved by targeting interventions at homes with poor energy efficiency (low SAP).
- Caution is required not to adversely indoor air quality by reducing ventilation rates during energy efficiency upgrades. However, the overall balance between positive and negative health impacts depends on the specific circumstances (e.g. local outdoor air quality, smoking vs. non-smoking households, high vs. low radon areas).
- The modelling suggests that some contribution to the total cost of improving the energy efficiency of the housing stock by the health sector/ society may be justified, especially for energy efficiency interventions targeted at homes with low energy efficiency.

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6 Appendices

6.1 Modelling team

The modelling team and their expertise are summarized in the table below.

Person (institution)	Experience and expertise
LSHTM	
Paul Wilkinson (Professor of Environmental Epidemiology)	Researcher in environmental epidemiology with long-standing interest in excess winter deaths, with multiple contributions in this area particularly for the UK. Expertise: topic expertise (excess winter death), study design and methods for quantifying the effect of seasonal/ cold-related risks and modification by social, environmental and other factors.
John Cairns (Professor of Health Economics)	Economist with more than 35 years research experience, more than 25 years specialising in health economics. Previously led a team of health economists undertaking economic modelling for cancer guidelines. Expertise: economic assessment: cost-benefit analysis
Zaid Chalabi (Senior Lecturer in Health Impact Analysis and Modelling)	Mathematical modeller with wide expertise in environmental health risk assessment, health impact analysis, cost-effectiveness analysis, value of information and uncertainty analyses, and decision analysis. Expertise: evidence regarding cost-effectiveness (CE) of methods to identify at risk populations; CE of interventions to prevent excess mortality & morbidity; CE of systems for delivery and implementation of approaches to prevent excess mortality & morbidity
James Milner (Lecturer)	Researcher with interests involving modelling the interactions between the urban environment and health, including the effects on health of air pollutants, and indoor air quality and housing. Has also developed techniques to assess the health impacts of changes in environmental exposures due to climate change mitigation policies in different sectors of society, including the housing sector. Expertise: modelling of health impacts, especially with regard to housing related health risks
University College London	
Mike Davies (Professor of Building Physics and the Environment)	Mike Davies has extensive research experience in the monitoring and modelling of building performance and seeks to understand how buildings can optimally minimise their production of CO_2 whilst maintaining healthy and comfortable conditions. He leads the team which are the UK representatives for the International Energy Agency Annex 55 work which aims to address the uncertainties associated with attempted improvements to the energy efficiency of national housing stocks. Expertise: indoor environment and the impact of interventions affecting exposures relevant to human health
Ian Hamilton (Lecturer)	Ian Hamilton is a Lecturer at the UCL Energy Institute, with research focused on energy use in the urban environment, including the impact of energy efficiency interventions in the domestic stock. He is a principal researcher on the EPSRC 'New Empirically-Based Models of Energy Use in the Building Stock' and he is working with the London School

	of Hygiene and Tropical Medicine to develop a model for DECC that quantifies the health impact of introducing energy efficiency measures within the UK's housing stock. Expertise: modelling of housing-related indoor exposures, health impacts and costs of interventions
Payel Das (Research Associate)	Payel Das is a research associate in the Bartlett School of Graduate Studies at UCL. Her research focuses on determining optimal energy efficient solutions for residential dwellings in the context of uncertainty, through a combination of building physics models examining indoor environmental quality, health impact assessment, and optimization algorithms. She has been involved in the development of probabilistic tools to aid retrofitting projects as part of the International Energy Agency's Annex 55. Expertise: modelling of housing-related indoor exposures, health impacts and costs of interventions

6.2 Description of the building model

6.2.1 Housing stock and energy performance

Housing stock

The economic model uses the EHS 2010/ 11 house and household stock as the basis for the modelling. The EHS provides a statistically random representative sample of the English stock on which the health impact of energy efficiency interventions can be modelled.

The EHS survey collects information on the overall condition of English homes and the households living in them. The survey provides data on key housing stock characteristics (including age, type and size) and households (age, tenure, number of occupants, income, vulnerability) based on physical surveys and interviews undertaken between 2010 and 2011. The surveyed 'dwelling sample' of properties where physical inspections were carried out contains 16,150 occupied or vacant dwellings, or 0.7% of the housing stock of 22.2 million dwellings in England (CLG, 2010). The EHS provide a factor with which to weight variables in order to represent houses or households in England. For the purpose of the modelling we use the houses weighting as these represent the occupants of the dwellings that will be affected by energy efficiency improvements.

The EHS includes details on the household occupants of the surveyed houses. The occupant details include their age, sex, employment status, smoking practices, income and a number of other features. Variables used in the model relate only to age, sex and whether an active smoker lives in a house.

Converting the EHS for building efficiency modelling input

In order to use the EHS housing stock data in the building efficiency modelling, the EHS data must undergo a conversion process in order to create a set of key input variables required for calculating the ventilation characteristics and thermal performance (DECC et al., 2012). The model uses SAP as the core calculation method to predict the ventilation, fabric heat loss, and heat system efficiency.

The conversion process converts variables collected in the EHS in order to infer features that are necessary to run a SAP-like estimation of the building efficiency. These include details such as: Dwelling and Household Information, Geometry, Ventilation, Other Heat Loss Elements, and Space Heating, see Table 39 below, which are used in the building efficiency modelling.

Table 39 - Building characteristics and components from EHS conversion

Characteristic	Component
Geometry	Gross floor area (GFA), volume, number of storeys, storey height, façade area, fabric component area (glazing, doors, party walls, roof, ground floor)
Glazing	Type, draught proofing
U-values	Glazing, roof, external walls, party walls, doors, thermal bridges, thermal mass parameter
Walls	Wall type, thickness,

Infiltration	Floor, fabric, draught lobby, additional infiltration, chimneys, flues, fans and passive vents
Heat system	Type, efficiency

The above conversion process is fully described in 'Converting English Housing Survey Data for Use in Energy Models' (DECC et al., 2012), produced for DECC by Cambridge Architectural Research, University College London, and Loughborough University. The output of the conversion process is a dataset of dwelling characteristics for each variant in the EHS that is used in the building efficiency modelling.

Efficiency modelling

The building efficiency modelling covers several aspects: fabric heat loss, heating system, ventilation heat loss and an estimate of overall energy performance. This information is then used to describe the relationship between the whole house efficiency (fabric, ventilation and heat system) and indoor temperature and to inform the prediction of indoor pollutant exposure levels in the exposure modelling. Figure 10 shows the interactions of the components of the building efficiency modelling. Note that the infiltration characteristics are used in the building pollutant modelling.

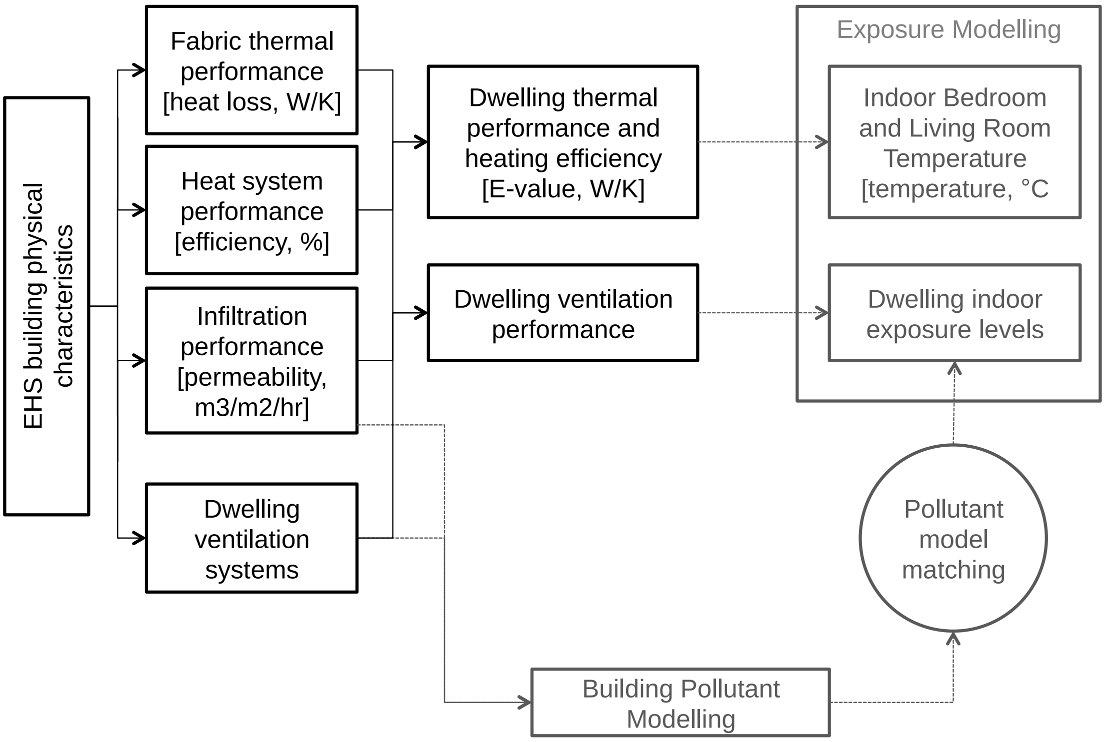

Figure 10 - Building efficiency modelling components

The whole house efficiency, which includes fabric, ventilation and heat system performance, is used to predict the internal temperature of the living room and bedroom using a method described in Oreszczyn et al. (2006), which established a relationship between dwelling heat transfer characteristics (referred to as an 'E-value') and internal temperature of the bedroom and living room standardised for an external temperature of 5°C. The ventilation performance is used to predict the dwelling permeability and ventilation heat loss. This process is fully described elsewhere (Hamilton et al., 2011). The permeability and ventilation system performance is used in the building exposure modelling to estimate the level of exposure to indoor pollutants.

Fabric performance

The inferred EHS dwelling characteristics are used to generate the dwelling fabric heat loss performance. Details of the dwelling component geometries (i.e. wall, window roof, floor areas) are drawn from the EHS and, along with characteristics such as wall type, age and location, are used to infer a heat loss coefficient (U-value, measured in W/ m^2K). Each fabric component, e.g. external walls, windows, doors, ground floor, and their inferred U-values are used to establish the total fabric heat loss.

Infiltration heat loss

The fabric infiltration performance prediction relies on steps used in the SAP method (section 2 in SAP 2005 v9.81) that estimate the air change rate of the dwelling due to infiltration. The infiltration for each dwelling component is inferred using the method described in DECC (2012).

The infiltration is used to predict the number of air changes in an hour within a dwelling. The overall air change rate (i.e. including the contribution from purpose provided ventilation systems) is used to determine the ventilation heat loss (measured in W/ K).

Fabric infiltration performance

The number of infiltration-related air changes (ach^{-1}) is also used to infer the permeability of the dwelling using the SAP method of converting to air tightness at 50Pa. The value represents the air movement across a metre-squared of fabric within an hour period (measured in m^3/ m^2/ hr).

The permeability is used to inform the estimates of the exposure levels experienced within a dwelling using the matched ventilation type and exposure models (described in the building pollutants modelling section below).

Heating system performance

The heat system efficiency is determined by first identifying the heat system type by using details of the heating system variables in the EHS. These details are used to identify features such as heat system efficiency in product characteristic databases, where available – see page 16 of DECC et al. (2012). The heat system efficiency is described as a factor ranging from 0 to 1 that describes seasonal efficiency (i.e. the mean efficiency through an annual period) of 1 unit of fuel conversion to useful heat output.

Dwelling heat transfer characteristic (E-value)

The above estimated fabric and ventilation performance is combined with the heat system to predict the dwelling heat transfer characteristic, referred to as an 'E-value' (after Oreszczyn et al., 2006).

The E-value is used to predict the living room and bedroom temperature, using a relationship described by Oreszczyn et al. (2006) and subsequently by Hamilton et al (2011) that takes into account the efficiency of the whole dwelling along with the expected behaviour of the occupant in setting and maintaining an internal temperature when standardised to an external temperature of 5 degrees.

The heat system efficiency, μ is used to modify the fabric and ventilation performance in order to express the actual heat required to maintain a 1 degree temperature difference that includes the performance of the heating system in converting fuel to useful heat, measured in Watts/ Kelvin. In this implementation of the model we include both fabric and ventilation heat losses. The ventilation infiltration is included in the 'E-value' by converting into a heat loss, where N is the number of air changes, V is dwelling volume and 3 represents the product of specific heat capacity of air and the density of air, converted to Watts, and i is each component of the building fabric. The whole house efficiency can be expressed as:

$$\text{E-value (W/ K)} = [(\Sigma U_i A_i) + (NV/ 3)]/ \mu$$

Dwelling ventilation systems

Details pertaining to the ventilation system present in the dwelling are limited in the English Housing Survey. For example, no details regarding the presence of trickle vents are contained within the variables collected and therefore it is necessary to infer the ventilation system likely contained within a dwelling. We use a set of rules to determine the possible presence of extract fans and trickle vents using details from the EHS (i.e. working extract fans), dwelling age (i.e. new dwellings include both extract fans and trickle vents to achieve Part F compliance), along with a random selection of pre-1990 dwellings to have trickle vents based on analysis of Warm Front surveys. The rules are applied to create a variable that describes the ventilation system features for the purpose of matching the EHS dwellings to the ventilation pollutant exposure model outputs.

6.2.2 Indoor environmental conditions

The following section provides an overview of the modelling approach to indoor air quality and the thermal environment.

Overview of building physics models for indoor pollutant concentrations

Results from the building physics model simulations for a set of dwelling archetypes are used to generate polynomial models to interpolate between modelled permeability bands that estimate the concentration of indoor pollutants. Figure 11 below illustrates the interactions of the components of the building pollutants modelling.

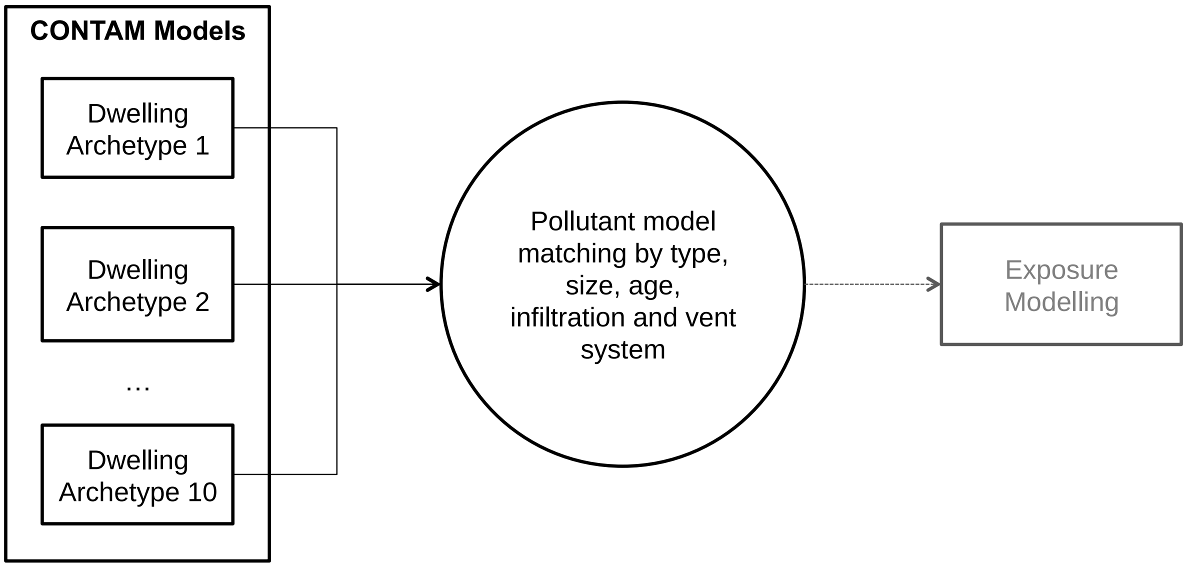

Figure 11 - Building pollutant modelling components

CONTAMv2.4c, a validated multi-zone airflow and pollutant transport simulation tool (Emmerich, 2001; Haghighat and Li, 2004; Walton and Dols, 2006) was used to model changes in indoor concentrations of pollutants in a representative set of English dwelling archetypes with different combinations of ventilation components. Guidance in Approved Document Part F (ADF 2010) (HM Government, 2010b) has been used in the design of all ventilation components. All systems have been assumed to be functioning correctly with no allowance made for mechanical failure or deterioration with time.

Pollution emission and deposition (for $PM_{2.5}$) profiles, drawn from the relevant literature, have been utilized for a range of airborne pollutants (Shrubsole et al., 2012). Modelling produces profiles of concentrations reported every 15 minutes, based on a 10-second integration time step.

Dwelling types

10 geometries were used for analysis of the English dwelling stock. Nine were derived from the LUCID project (Oikenoumou et al., 2010). The remaining geometry, House 7, was taken from (Wilkinson et al., 2009). We make the assumption that these archetypes are adequate to broadly represent the English domestic stock. The geometries consist of three flat-type archetypes and seven house-type archetypes. Each of the flats are assumed to be located at one of three floor levels (ground, first, second or higher).

External weather profiles, wind pressure coefficients, and internal temperatures

For all geometries, separate winter and summer weather files were constructed using CIBSE/ Met Office hourly data - Test Reference Year (TRY) and Design Summer Year (DSY) (CIBSE and UK Met Office, 2010). Dynamic indoor temperature profiles were informed by a study from FMNectar (FMNectar, 2007), which investigated ventilation effectiveness in support of Part F of the Building Regulations.

We assumed that all buildings are orientated north/ south, as it has been shown in previous work that orientation only has a maximum effect of reducing or increasing $PM_{2.5}$ concentrations by 3.7% (Shrubsole et al., 2012). For the houses, the facade with the front door is assumed south-facing. For flats, the front facade of the building - as defined by the LUCID project (Oikenoumou et al., 2010) - is assumed to be south facing. A variable wind pressure profile (dependent on wind speed and direction) suitable for long walls was applied to all building openings in the modelling (Swami and Chandra, 1987). Wind speed modifiers were applied based on the building height and adjusted for an urban location with flats assumed to be on the ground floor for the purpose of pollutant.

Ventilation strategies

Dwelling fabric infiltration in the models is modelled via openings (cracks). Two openings (one high, one low) are placed in each external wall, floor and roof, with gap sizes proportional to the facade wall area (Orme and Leksmono, 2002) and the whole dwelling permeability. In flats, floors and ceilings are assumed to be impermeable, and therefore there is no air flow across them. In houses, air flow is possible between floors, and the floors and the attic and cellar. Attics have ventilation in the eaves, and cellars are vented with air-bricks (both complying with BS 5250 (BSI, 2011)) to allow for exchange of air with the external environment.

The modelling addresses four ventilation strategies, including:

1. *No trickle vents or extract fans*: ventilation is achieved via the infiltration component and periodic purge ventilation by window opening. This excludes trickle vents and extract fans, except in dwellings with no windows present in the kitchen and bathroom, where extract fans are required.
2. *Trickle vents and extract fans:* ventilation is achieved via the infiltration component, trickle vents, extract fans, and periodic purge ventilation by window opening. This strategy represents properties refurbished to, or constructed in line with ADF2010.
3. *Trickle vents:* ventilation that includes the infiltration component, trickle vents and periodic purge ventilation by window opening, but excludes the extract fans, except in dwellings with no windows present in the kitchen and bathroom.
4. *Extract fans:* ventilation, which excludes the trickle vents but includes extract fans, the infiltration component, and periodic purge ventilation by window opening

The EHS does not contain any information on the presence of trickle vents. It is assumed that all dwellings built post-1990 are built with trickle vents. Analysis of Warm Front dwellings showed that approximately 8% of pre-1990 dwellings had glazing units with trickle vents. To account for this, a random selection of pre-1990 dwellings was modelled with trickle vents installed and working.

Adventitious openings/infiltration component

Models were constructed with permeability values of 3, 5, 7, 10, 15, 20, 25 and 30 $m^3/m^2/hr$ at 50Pa representing the variation observed in the UK (Stephen, 2000). This resulted in 320 CONTAM models for the summer months, and a further 320 for the winter months, and therefore 640 in total.

Ventilation components

Extract fans and trickle vents were specified to comply with Approved Document F of the Building Regulations for England (ADF 2010) (HM Government, 2010b).

Contaminants

Five contaminants are modelled: environmental tobacco smoke (ETS), $PM_{2.5}$ from internal sources $PM_{2.5}$ from external sources, radon, and moisture (as a precursor for mould). A series of pollutant sources and sinks were placed within appropriate building zones. External concentrations of pollutants were specified where relevant. The CONTAM models then predict the concentrations of the pollutants within each building zone every 15 minutes for a year. Models were created only for the ground-floor flats and the radon concentrations for first-floor flats were assumed to be half this, and for second-floor or higher flats were assumed to be zero (Milner et al., 2014).

Matching the archetypes to the EHS

The CONTAM model permutations, based on the range of geometries, permeabilities, ventilation strategies, and seasons, resulted in a set of 640 archetypes. Adding variations in the floor level of the flat gives 1024 archetypes in total. These are then matched to the EHS using a set of rules to determine which archetype is a suitable match in terms of its physical parameters and ventilation characteristics, including: dwelling type, size (GFA) and ventilation system. The first rule matches via the surveyed dwelling type (i.e. flats, terraced houses, bungalows and detached houses), to ensure that the geometric form modelled in the building model broadly represented a given dwelling. The second rule used gross floor area to match archetypes where there were multiple dwelling types (i.e. terraced houses). Matching for flats was further subdivided by considering those on the ground floor and below, those on the first floor, and those on higher levels to enable variations in radon concentrations with height. Flats on the ground floor and below received the full concentration of radon (weighted for the stock), those on the first floor received 50% of the ground floor exposure, and those above the first floor and above had no exposure to radon.

Exposure modelling

The exposure modelling generates estimates for the environmental conditions experienced within the EHS variants, these include: indoor temperature, risk of mould growth, environmental tobacco smoke, $PM_{2.5}$ from indoor and outdoor sources and radon. Though geographical variations and the incidence of radon prevention/ mitigation measures in the stock are not considered in this modelling study, the overall distribution of radon exposures is calibrated against the distribution for the UK (Gray et al., 2009). These baseline exposures are derived by applying equation parameters from polynomial models developed in the pollutant modelling and a relationship between indoor temperature and building efficiency, further described below. The exposure predictions are based on two building parameters that are derived through a SAP methodology, E-value (fabric performance over heating system performance) and permeability. The EHS derived values of these parameters are compared to other known distributions. The E-value is compared against a distribution found from a Warm Front analysis (Oreszczyn et al., 2006a) and the permeability is compared against both Warm Front and the Stephen's (BRE) distribution, see Figure 12 below.

6.2.3 Energy efficiency intervention eligibility

The effect of the interventions on the indoor environmental conditions of the dwelling are determined by the change in the determinant of the exposure (i.e. thermal or indoor air quality). Changes in exposures are made through the introduction of energy efficiency measures to those dwelling that are determined as being eligible for an efficiency retrofit. The measures reflect interventions that are identified under various UK Government initiatives, including the Green Deal, ECO and CERT.

Dwellings are deemed eligible based on rules that relate to each component or where an EHS variable exists. The rules for each measure are:

- Lofts to 250mm: EHS variable (EPulin05e) 'Energy upgrade loft insulation' recorded as 'Yes'
- Solid Wall Insulation: EHS variable (wallinsx) 'type of wall and insulation' recorded as 'other'
- Cavity Wall: EHS variable (wallinsx) 'type of wall and insulation' recorded as 'cavity uninsulated'
- New Double Glazing: Modified EHS variable (typewin) 'Predominant type of window' combined to form three groups, single, double, mixed, recorded as 'single'
- Install Condensing Boilers: EHS variable (EPublr5e) 'Energy upgrade boiler' recorded as 'Yes'
- Install Gas Central Heating: EHS variable (heat7x) 'primary heat system type' recorded as 'room heaters' or 'portable heaters'
- Temperature adjustment: Direct temperature adjustment to EHS selected sample
- Draught Stripping: All dwelling are eligible for a degree of draught stripping, with further draught proofing if infiltration due to floors > 0.1 and percent glazing draught proofed <0.98
- Trickle vents: All dwellings with no trickle vent or extract fan systems or extract fan only systems
- Extract fans: All dwellings with no trickle vent or extract fan systems or trickle vents only

The measures are applied by altering key parameters within the Building Efficiency Module. Table 40 provides values of the adjusted parameters. Sources for the parameters include RdSAP version 9.83 (BRE and DECC, 2009), which provides several tables relating to u-values of dwelling components with varying levels of energy efficiency. For infiltration adjustments, relevant data are sparse in the literature but we have used figures informed by research from Warm Front that assessed the impact of energy efficiency measures on airtightness is used to determine the adjustment to infiltration rates within a dwelling post-intervention (Hong et al., 2004).

Table 40 - Energy efficiency measures parameter adjustment values

Intervention	Component	EHS variable	Value	Unit	Source
Lofts to 250mm	insulation	roof uvalue	0.2	W/ m2 K	RdSAP v9.83 2005
	infiltration	direct adjustment	0.1	Nach	Hong et al, 2004
Wall Insulation (Solid External)	insulation	external wall u-value	0.58	W/ m2 K	RdSAP v9.83 2005
	infiltration	direct adjustment	0.2	Nach	Hong et al, 2004
Wall Insulation (Cavity fill)	insulation	external wall u-value	0.33	W/ m2 K	RdSAP v9.83 2005
	infiltration	direct adjustment	0.2	Nach	Hong et al, 2004
Double Glazing	insulation	glazing u-value	2	W/ m2 K	RdSAP v9.83 2005
	infiltration	draught stripping percentage	0.98	Nach	RdSAP v9.83 2005
Install Condensing Boilers	efficiency	main system efficiency	93	%	RdSAP v9.83 2005

Install Central Heating	temperature	direct temperature adjustment	0.00395	°C	Oreszczyn et al. 2006
	efficiency	main system efficiency	92	%	RdSAP v9.83 2005
Draught Proofing	infiltration	floor infiltration	0.1	Nach	RdSAP v9.83 2005
	infiltration	glazing draught stripping percentage	0.98	Nach	RdSAP v9.83 2005
	infiltration	direct adjustment	0.2	Nach	Hong et al, 2004

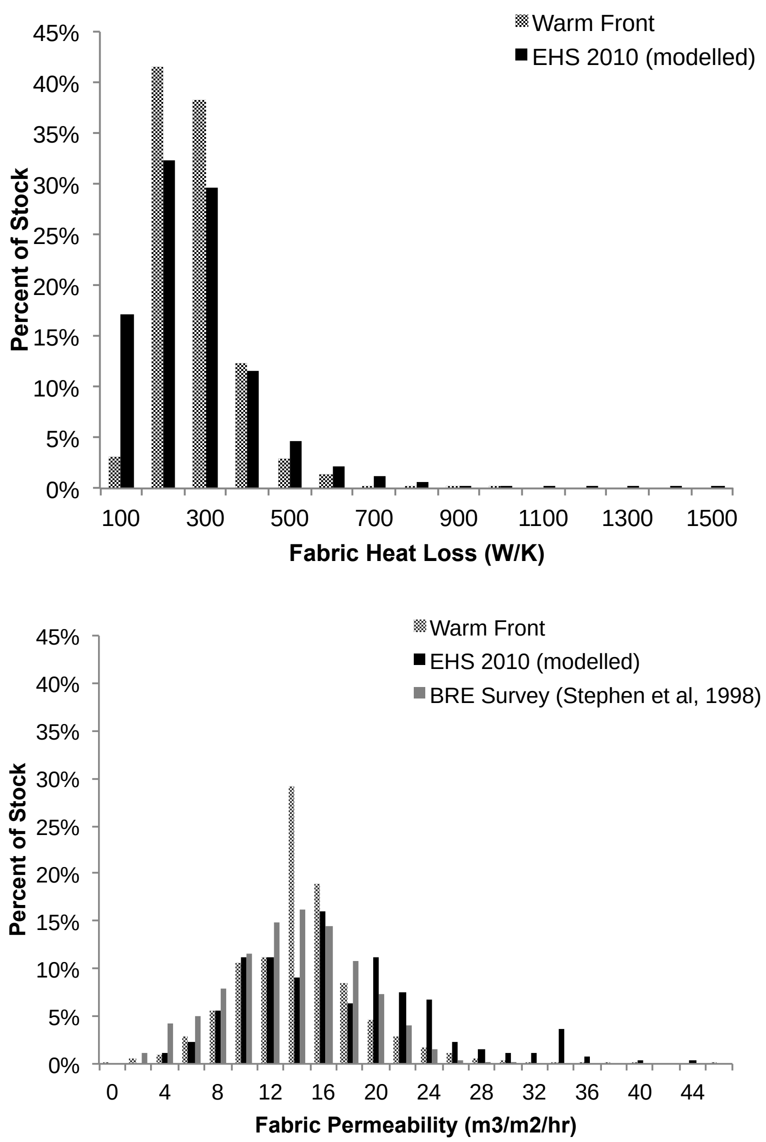

Figure 12 - Comparison of fabric heat loss and permeability distributions for EHS, Warm Front, and Stephen's BRE housing stock

The exposure modelling also includes energy efficiency scenarios that, when applied to the selected stock sample, generate a modified exposure. The changes in exposure are derived by comparing the base exposure to the modified exposure, either as no change, increased or decreased. These changes in exposure are then fed into the health model by applying each exposure change to the occupants of the EHS house variant.

Indoor temperature

An estimate of the indoor temperature, which includes a rebound or temperature take back effect was based on analysis of data from an evaluation of the government's Warm Front domestic energy efficiency scheme[6], described fully by Oreszczyn et al. (2006) and subsequently by Hamilton et al.

[6] The national evaluation gathered detailed indoor environment and energy efficiency data from a subset of ~1600

(2011). The Warm Front evaluation established a relationship between dwelling heat transfer characteristic (E-value) and indoor living room and bedroom temperature when standardised at 5 °C external, see Figure 13 below.

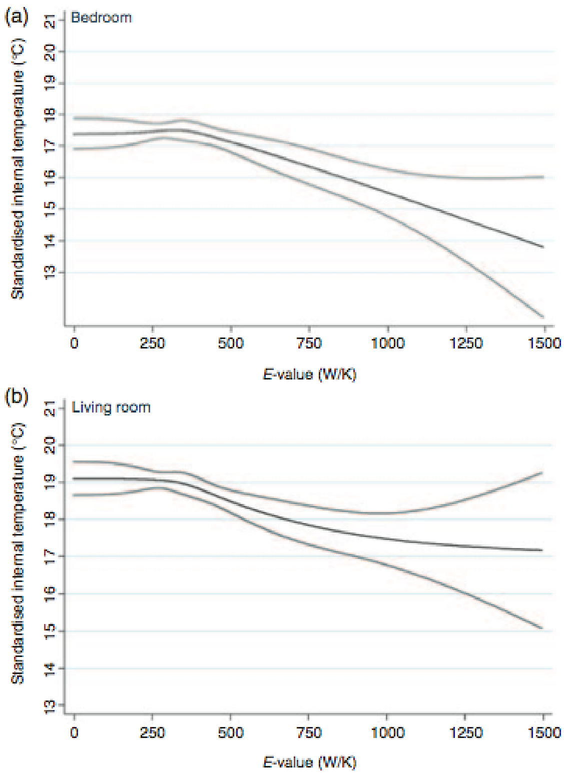

Figure 13 - (a) and (b) Standardised internal temperatures (with upper and lower 95% confidence intervals) for Warm Front dwellings (modified from Oreszczyn et al. 2006)

As in Hamilton et al. (2011), in this model we assume that an average of the standardised living room and bedroom temperatures provides a useful estimate of heating season average whole-house temperatures. The values are not weighted or adjusted for other possible modifiers. This averaged temperature is also used to determine the vapour pressure excess within the dwelling for the risk of mould severity index >1.

Risk of mould

To calculate the probability of a dwelling having a mould severity index >1, a relationship found in Warm Front that uses the standardised relative humidity (see Figure 14 is applied to each EHS variant. This method uses a combination of the moisture content modelled in CONTAM, and the predicted internal temperature, and is based on ISO 13788 'Hygrothermal performance of building components and building elements -- Internal surface temperature to avoid critical surface humidity and interstitial condensation -- Calculation methods' (ISO, 2012).

dwellings. Winter indoor temperatures and relative humidity measurements were recorded every half hour during heating periods for at least 3 weeks by the use of data loggers located in the living room and main bedroom. The resulting data are one of the few sources that combine property thermal characteristics, monitored temperature, relative humidity and mould growth data.

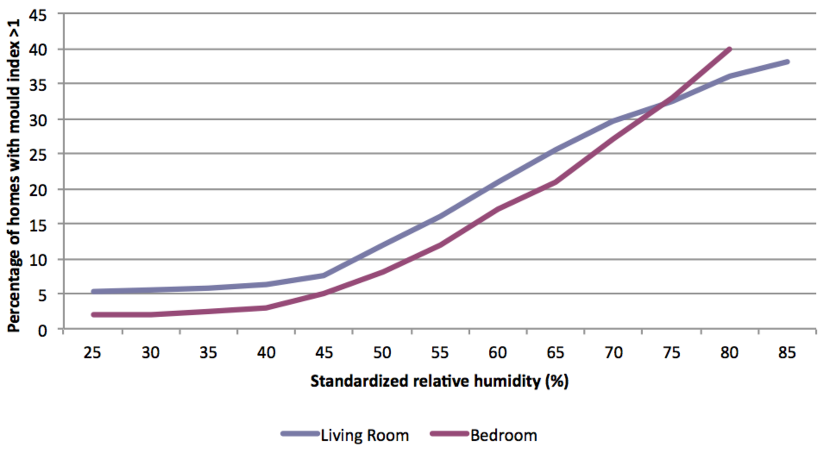

Figure 14 - MSI and standardised internal relative humidity

Pollutant exposure models

Polynomial models that predict the concentration of each exposure (ETS, indoor and outdoor $PM_{2.5}$, and radon) are derived for each of the ventilation case types (i.e. geometry x ventilation system x floor height).

An absolute baseline concentration level is predicted for each dwelling variant in the EHS for a given permeability using the polynomial models. The concentrations are revised according to the application of energy efficiency measures for any selected sample of dwellings or households. The change in concentration drives the health impact.

6.2.4 Targeting of interventions

Long-standing illness and disease are included under the Disability section of the face-to-face component of the household interview. Household age is coded for each household member. Household income is derived from interview data. Table 41 provides a description of how these are coded.

Table 41 - EHS Household variable description

People
Sex *Code first that applies* (1) Male (2) Female
DteofBth *What is your date of birth* For day not given… enter 15 for day For month not given… enter 6 for month DATE
Ageif ASK IF: DteofBth <> EMPTY AND: (DteofBth = DONTKNOW) OR (DteofBth = REFUSAL) *What was your age last birthday?* 98 or more = Code 97 0..97

Disability
LSILL *Do you have any long-standing illness, disability or infirmity – by long-standing I mean anything that has troubled you over a period of time or that is likely to affect you over a period of time?* (1) Yes (2) No
[ASK IF: LSIll = Yes] **Dstyp1** (multicoded variable delivered as indicated below) *What type of illness or disability do you/does [name] have?* CODE ALL THAT APPLY (0) No (1) Yes (-8) No answer (-9) Does not apply (1) Vision (DsVision) (2) Hearing (DsHearing) (3) Learning difficulty (DsLrnDf) (4) Mobility (DsMobility) (5) Breathing problems (DsBreath) (6) Heart disease (DsHeart) (7) Mental health problems (DsMental) (8) Other (DsOther) (9) Don't know (DsDKnw)
Income
Hhincx *EHS Basic Income (annual net household income (HRP + Partner) including savings)* £ N.B. The EHS Basic Income refers to the annual net income of the Household Reference Person (HRP) and any partner from wages, pensions, other private sources, savings and state benefits. Amounts are net i.e. after the deduction of Tax and National Insurance where applicable. This income variable does not include any housing related benefits/ allowances. Value derived from BRE income model. A total combined gross income of the HRP/ partner is calculated for each household that provided income data (private income + benefit income + savings income). Income Tax and National Insurance payable are calculated, where appropriate, and these amounts are deducted to give total net annual household income. Low incomes on the dataset are identified and brought up to at least basic income support (the justification for this being that it is likely that they are under- reporting their income for some reason; either deliberately or by mistake). Missing incomes of the HRP and partner are assigned based on the median income of key groups from the weighted EHS dataset. For more details see: 'EHS 2011 Dictionary of derived variables'

Chronic Obstructive Pulmonary Disease (COPD)

For COPD we cross-tabulated 'Long-standing illness' and 'Breathing problems' variables. Using the EHS variables LSILL=Yes and DsBreath=Yes, the prevalence of COPD risk among the English Household Population is estimated as approximately 5.4%. Estimates for England place COPD at 3.6% (males 4.5%, females 2.8%).

Heart disease

For heart disease we cross-tabulated 'Long-standing illness' and 'Heart disease' variables. Using the EHS variables LSILL=Yes and DsHeart=Yes, the prevalence of heart disease risk among the English Household Population is estimated as approximately 3.95% Estimates for England place heart disease at 5.8% (males 7.0%, females 4.7%).

Mental Health

For mental health, we used the 'Mental health' variable. Using the EHS variables DsMental=Yes, the prevalence of mental health disease among the English Household Population is estimated as approximately 1.92%. Estimates for England place Common Mental Disorder (CMD) at 16% (males

13.6%, females 19.5%).

Elderly households

For elderly households, we used the derived household occupant age variable. Using the EHS variable age => 65 to identify elderly households. The prevalence of EHS households with an elderly occupant is 12%.

Low-income

For low-income status, we used the 'Net Annual Household Income' variable. The lowest quintile of hhin5x=1 (i.e. 20%) is used to characterise low-income households.

6.2.5 Input parameters

Table 42 provides a list of key input parameters used in the building physics model (CONTAM).

Table 42 - Key input parameters used in CONTAM with sources

CONTAM	Variable	Value	Unit	Source
General	Number of occupants	Varies across stock	Integral	(Department for Communities and Local Government, 2012)
	Indoor temperature	Varies with time	°C	(FMNectar, 2007)
Geometry	Ground floor area	Varies across stock	m^2	(Department for Communities and Local Government, 2012)
	Height	Varies across stock	m	(Department for Communities and Local Government, 2012)
	Number of rooms	Varies across stock	Integral	(Department for Communities and Local Government, 2012)
	Number of storeys	Varies across stock	Integral	(Department for Communities and Local Government, 2012)
	Window dimensions	Varies across stock	m^2	(HM Government, 2010b)
	Door dimensions	2 × 0.8	m × m	(Oikonomou et al., 2012)
Outdoor conditions	Weather (dry bulb temperature, wet bulb temperature, atmospheric pressure, global solar radiation, diffuse solar radiation, cloud cover, wind speed, wind direction)	Varies with time	°C, °C, hPa, Wh/ m^2, Wh/ m^2, oktas, knots, degrees clockwise from North	(The Chartered Institution of Building Services Engineering, 2010)
	Wind pressure coefficients on building façade	Varies with orientation of façade	Unitless	(Swami and Chandra, 1987)
Ventilation	Building envelope permeability	Varies across stock	m^3/ m^2/ h@ 50Pa	(BRE, 2012; Department for Communities and Local Government, 2012)
	Door leakiness	1% of airflow	m^2	(Shrubsole et al., 2012)

		when door fully open		
	Ventilation system type	Varies across stock	Unitless	(Department for Communities and Local Government, 2012)
	Trickle vent size	Number varies across stock	Effective opening area: m^2	(HM Government, 2010b)
	Extract fan ventilation rate	Varies across stock	l/s	(HM Government, 2010b)
	Air bricks	Number varies across the stock	Open area: m^2	(BS5250 section 8.5.3)
	Loft ventilators	Varies across stock	Open area: m^2	(BS5250 section 8.4.2.2.3.2)
Contaminants	$PM_{2.5}$ deposition rate	0.39	/h	(Ozkaynak et al., 1996)6)
	$PM_{2.5}$ generation rate	1.6	mg/min	(Ozkaynak et al., 1996)6)
	$PM_{2.5}$ ambient concentration	13	$\mu g/m^3$	(Shrubsole et al., 2012)
	Radon emission rate	Varies across stock	Bq/m^3	(Fang and Persily, 1995; Gray et al., 2009)b)
	ETS emission rate	0.99	mg/min	(Afshari et al., 2005; He, 2004)
	Number of cigarettes smoked/day (indoors)	7	Unitless	(The NHS Information Centre, 2011)
	Moisture emission rate (sleeping) per person	40	g/hr	(FMNectar, 2007)
	Moisture emission rate (gas cooking)	3000	g/day	(FMNectar, 2007)
	Moisture emission rate (bathing and washing) per person	200	g/day	(FMNectar, 2007)
Schedules	Cooking time	15 minutes for breakfast and 30 minutes for dinner on a weekday, and an additional 30 minutes for lunch on weekends.	mins	(Wilkinson et al., 2009)
	Bathing time	Depends on number of occupants	mins	(Shrubsole et al., 2012)
	Smoking time per cigarette	5	mins	(Afshari et al., 2005; He, 2004)
	Window opening time	During cooking times in the kitchen and bathing times in the bathrooms in the winter, and additionally between 9am-5pm in the summer	mins	(Wilkinson et al., 2009)
	Time spent sleeping	8 hours in each bedroom	mins	(FMNectar, 2007)