1 The impact of home energy efficiency interventions and winter fuel payments on winter- and cold-related mortality and morbidity in England: evaluation of a natural experiment

2 Background

We propose the first adequately-powered population-based study to quantify the impact on cold-related mortality and morbidity (hospital admissions) of home energy efficiency interventions. It will address current critical knowledge gaps, and considerably strengthen the evidence base for appraisal of policy options in the housing sector which could see enormous investments over the coming decades.

2.1 Existing research

It has been long recognized that the UK has a large and unacceptable burden of excess winter mortality and morbidity (generally upward of 25,000 excess winter deaths each year), which is greater than that of many comparable northern European countries with colder climates. Although part of the winter excess is attributable to influenza and other seasonal infections, time-series studies suggest the major part of the seasonal burden is related to exposure to cold.[1,2] Theoretical considerations and some direct evidence from the UK, New Zealand and elsewhere suggest that housing may play an important role in determining that vulnerability,[3,4] though it is also recognized that exposures to cold through outdoor excursions may also be important. There has therefore been much interest in, and debate about, the contribution that interventions on housing quality may have on winter- and cold-related mortality and morbidity, especially in the context of rapidly worsening UK figures on fuel poverty (caused mainly by recent upward global trends in energy prices) and recent severe winters. Over the next few decades there will be major investments in the housing sector driven by (i) policies aimed at reducing household energy use and greenhouse gas (GHG) emissions to meet legally-binding obligations of the Climate Change Act (2008) and (ii) considerations of health, in particular the assumed benefits of improved insulation and energy efficiency for winter- and cold-related deaths and illness. However, these investments may be very costly, and they have potential for adverse as well as positive effects on health[5] if in part achieved through reduced ventilation.

In recent months, the Department of Energy and Climate Change (DECC) have commissioned work, led by the applicants, to examine how the health impacts of home energy efficiency might be modelled. A number of crucial evidence gaps were apparent. Among the most important is the lack of direct evidence on cold-related mortality and harder health outcomes such as hospital admission. Much of the scientific literature on home energy efficiency and health is dominated by small-scale, short-term assessments, often inadequately controlled, and using self-reported measures as key outcomes, including thermal comfort. While thermal comfort and mental well-being are important outcomes, it has proved difficult to synthesize the published evidence into robust estimates of clinical impact because of potential issues in some studies of uncontrolled confounding/bias, the transient nature of some forms of impact, and the indirect nature of some markers for clinical significance. Importantly, no study published to date has been able to make a direct assessment of the impact of home energy efficiency on mortality, and only to very limited to degree (mainly focused on specific patient groups) has any study examined emergency hospital admissions. Osman and colleagues have published mixed evidence in relation to COPD,[6,7] for example, and Jackson et al report some evidence for a package of housing and social service intervention.[4] The paucity of evidence is mainly because of the extremely large sample sizes needed to test such impacts (remembering that cold-related deaths and hospital admissions are only a small part of all deaths and admissions – and identifiable only through statistical comparisons) such that randomized controlled trials with mortality as the outcome are effectively precluded: for most population-based mortality and hospital admission outcomes, adequate power requires sample sizes in excess of 10^5 dwellings.

2.2 Rationale for current study

The very limited evidence relating to mortality and hospital admission is a major gap in knowledge, because of its central relevance to policies aimed at tackling excess winter mortality/morbidity in the UK, and to the major choices needed in housing policies in general given the transformative investments needed for climate change mitigation. Moreover, we cannot assess the full economic and NHS benefits of such investments because of reliance on old and untested assumptions.

However, because of several unique data sources in the UK, it is now possible to attempt an evaluation of mortality and hospital admission impacts through *natural experiment*. Key is the emerging availability of nationwide data on housing energy efficiency interventions compiled into a national database by the Energy Savings Trust (EST). This database is the Homes Energy Efficiency Database (HEED), which was established to 'help monitor and target carbon reduction and fuel poverty work'. HEED tracks house-by-house the sustainable energy characteristics of the UK's housing stock using data gathered from a wide range of sources including energy suppliers, government grant managing agents, local authorities, home energy checks as well as EST programmes (examples include EEC/CERT, fuel poverty programmes, Low Carbon Buildings Programme, CIGA, Corgi). HEED includes data on insulation measures, heating systems, appliances and micro-generation installations, along with property survey information. It now covers approximately 50% of the UK's homes (over 13 million homes) with property- and date-specific details of such energy efficiency interventions over the last decade or so. By linking, nationwide, to postcoded mortality and hospital admission statistics, this data base for the first time makes it possible to address the evidence gap on the relationship between home energy efficiency and cold mortality/morbidity through direct measurement in a well-powered empirical study. It will provide important new empirical evidence relevant to a wide range of policy areas, including health protection, housing policies, and NHS demands and costs; and evidence on the potential for housing investment to reduce health inequalities.[8] It has the potential to be a key element in decisions on major areas of policy formulation over coming years.

Why support this proposal The proposed study fulfils the key criteria for evaluation of a natural experiment.[9] It addresses a form of intervention with potential to affect a very large but preventable burden of ill health and mortality in the UK related to poor housing which is not readily amenable to a randomized trial of the required scale. It should make a major contribution to the scientific literature internationally: the first study in the world literature to provide adequate basis for quantifying the impact on ‘hard’ health outcomes of energy efficiency improvements in the general population. Its findings could make a crucial addition to the evidence base for testing policy in an area where few of the many assumptions of impact are supported by empirical evidence. It focuses on a sector which is likely to be the target for very large (multi-billion pound) investments both by government and the private sector over the next two decades, and where good evidence is essential to maximize the benefits and minimize potential harms. It assesses the impact on health of investment outside the health sector, which increasingly will be important to an integrated public health strategy. It will be relevant for the future development of the cold weather plan.[10]

In addition to the main research questions the study will also provide evidence on:

- the impact on winter- and cold-related mortality/morbidity of winter fuel payments (within the context of the effect of fluctuation in domestic fuel prices)
- the impact on the health service of winter/cold-related burdens (costs, winter pressures on the health services) and the potential gains from policies aimed at improved home energy efficiency
- the cost-benefit (assessed within a formal multi-criteria decision analysis framework) of home energy efficiency interventions, taking account of impacts on the health service and the value of averted quality-adjusted years of life lost
- the unintended positive and adverse effects of home energy efficiency interventions
- the impact on inequalities in health & fuel poverty
- the nature of the general relationship between cold weather and adverse health impacts

The project builds on substantial methodological and evaluation research experience by the applicants, developed through on-going and recent research projects including (among others) an MRC project on *methods for quantifying weather-health relationships;* an NERC project on *air pollution and weather-related health impacts* (AWESOME), which is developing methods for characterizing the indoor environment in relation to housing characteristics; a multi-partner EC-funded project (‘PURGE’) which is examining the impacts on health of greenhouse gas reduction strategies in urban environments (following the work of the *Task Force on Climate Change Mitigation and Public Health)*, and a recent project examining the methods for quantifying the health impacts of home energy for DECC.

PLAN OF INVESTIGATION

The project is a ‘natural experiment’[9] study of the effect on health of the introduction of home energy efficiency (HEE) measures to English dwellings over the last decade.

3 Research objectives

Aim: to evaluate the impact on winter- and cold-related mortality/morbidity of home energy efficiency interventions in England, including assessment of the impact of fuel costs and subsidies.

Specific objectives:

(1) To link HEED data for England, 2000-2010, to postcoded national mortality and hospital admissions (HES) data and to location-specific daily meteorological data to quantify the degree to which cold temperature-mortality/hospital admissions relationships (overall and cause-specific) are modified by the introduction of HEE measures;

(2) To use 35-year series of data for the major conurbations of England to assess inter-annual variations in cold mortality/morbidity and the degree to which they are influenced by fluctuations in fuel price and the winter fuel payments, especially for vulnerable population groups defined on the basis of socio-economic status, age and other parameters;

(3) To conduct in-depth interviews with householders and households to document long term experiences and behaviour changes associated with HEE interventions, with a focus on the pathways linking HEE, wellbeing and aspects of fuel poverty, and to explore how health evidence of HEE interventions is, and could be, utilised in policy and advocacy activities including on inequalities;

(4) To use the evidence of (1) to (3), in combination evidence on costs and existing epidemiological evidence, to elaborate a model of health impact and to present and test policy options using a formal multi-criterion decision analysis (MCDA) framework;

(5) To maximise knowledge transfer and research impact by using a model of user-involvement which engages with major stake-holders throughout the research process.

4 Research design

The study will use detailed data from the Home Energy Efficiency Database (HEED), a national database developed by the Energy Saving Trust (EST) that records, at individual-dwelling level, HEE interventions (forms of insulation, heating system upgrades etc). This database, compiled from multiple sources, including government scheme management agents and local authorities, contains data on over 13 million homes, or around 50% of the UK housing stock with a date stamp and dwelling code for each intervention (currently some 160 million records). HEED is broadly, though not 'statistically', representative for home tenure when compared with other national level datasets. The level of private ownership is therefore reasonably, but not exactly, representative of that in the housing stock as a whole. We will build on existing collaboration with database holders EST to link it to postcoded mortality and hospital admissions data to enable us to quantify the impact of the introduction of HEE measures on cold-related mortality and morbidity. It will be the first large-scale study to attempt such direct quantification.

Analysis for objective 1 is essentially a controlled interrupted time-series, with separate before-after time points defined by the date of each of the millions of energy efficiency interventions made to dwellings throughout England since 2000. Because these interventions are scattered geographically and temporally, the population without such interventions can function as a control. The comparison will not be simply of overall mortality and morbidity, but of specific cold-related mortality and morbidity determined using time-series and related (case-crossover/case only) methods to which the applicants have made substantial methodological developments. We will use detailed location-specific daily meteorological data. Categorization of the effect of the different forms of housing intervention on the indoor environment will be obtained from existing empirical data and building physics modelling. We will further quantify (using empirical data) the impact of HEE measures on fuel savings and refurbishment expenditure, and changes in comfort levels. Specific linkage will be made to properties upgraded through the Warm Front programme that have been subject to earlier detailed temperature measurements and health surveys. Objective 2 requires long time-series because of the focus on inter-annual variations. Domestic energy price data will be obtained from DECC. Time-series methods will control for long-term trends and annual/seasonal factors (influenza, vaccination coverage, preceding seasonal mortality, air pollution etc). Subgroups defined by small-area socio-economic markers will enable us to compare impacts across deprivation levels.

The qualitative component will focus on long-term follow-up (post-one year) after HEE interventions to examine reported behaviour change, how this is likely to be linked to well-being and how household decisions about HEE are made. Analysis of interviews will help provide evidence on unintended positive and negative effects and on the processes by which psychosocial impacts are achieved. A purposive sample of around 50 households will be recruited from three contrasting areas, using a sampling grid to include those from a range of households (by size, housing tenure, housing stock type, area deprivation) and time since intervention. The potential policy impact of the research evidence on health impacts from this and other studies will be explored through focus groups with stakeholders including national and local policy makers, voluntary sector organisations, the private sector (e.g. energy and building companies), and householder/tenant groups.

5 Study population

Participants are the population of England covered by the Home Energy Efficiency Database (approx.13 million homes) who have had home energy efficiency upgrades since 2000. Comparators are the residents of those same dwellings before energy efficiency interventions were introduced. Because these myriad interventions are scattered geographically and temporally over the 11 year period of study, the pre-intervention population can function as a control, both cross-sectionally and over time. The chief outcomes include: cold-related mortality and hospital admissions (by cause, and for vulnerable subgroups defined on the basis of socio-economic status, age and other parameters). We will quantify specific cold-related mortality and morbidity using time-series/case series methods based on linkage of post-coded health data to weather data. From this we will quantify the 'step changes' in cold-mortality/morbidity relationship associated with HEE improvements (controlled interrupted time-series).

6 Socioeconomic position and inequalities

Health burdens arising from inadequate home heating and insulation are often viewed as a socio-economic problem relating to fuel poverty.[11] [12] This study will provide detailed evidence on various aspects of this question, including (i) the current socio-economic inequalities in burdens of cold-related mortality/morbidity, (ii) the contribution that HEE interventions has made to reduction in those socio-economic inequalities over the period 2000 to 2010, and (iii) an assessment of the *potential* future impact on such inequalities of policy options assessed through the multi-criteria decision analysis (MCDA) model. Health inequalities is an explicit assessment criterion of the MCDA (see section 10).

7 Planned intervention

The intervention comprises home energy efficiency (HEE) improvements (improved insulation, heating system upgrades, and micro-generation installations) introduced in England since 2000, and recorded in the Energy Saving Trust (EST) Home Energy Efficiency Database (HEED). These improvements were made by a range of providers, and through a variety of different schemes, many supported by government or local authority grants. HEED data are gathered from energy suppliers, government grant managing agents, local authorities and other landlords, home energy checks and EST programmes.

Setting England. Approx.13 million dwellings (~50% of total) covered by the HEED database.

Delivery of the intervention The study is of past (2000-2010) home energy efficiency interventions implemented through a variety of funding mechanisms, including HEE programmes targeted at low income families and those at risk of fuel poverty (e.g. the *Warm Front* scheme). They typify interventions currently being further developed as part of major areas of government policy to address public health burdens and greenhouse gas (GHG) emissions reductions.

Funding of the intervention The evaluation is of recent past HEE measures, supported by grants from various sources (government, local authorities, voluntary bodies) and private investment. There is no new intervention or cost.

8 Proposed outcome measures

Cold-related mortality, hospital admission; overall (not specifically temperature-related) mortality and hospital admission; heat-related mortality and hospital admission. All by cause, age-group and socio-economic group in relation to home energy intervention status. Household energy use and cost; intervention costs; GHG emissions. Results of a multi-criteria decision analysis (MCDA) model for comparing home energy efficiency policies across health (summarized as QALYs), health inequalities (distributions of QALYs) and other non-health criteria (e.g. costs, CO2 emissions, energy use).

9 Assessment of harms

Empirical evidence will be obtained on a selected range of potential adverse outcomes, summarized below. In addition, changes in relevant exposures (e.g. indoor air quality, costs) will be derived from building physics models parameterized by HEED data. Indicative likely impacts on health over a 20 year horizon will be estimable from the health model used to inform the MCDA (important for radon-related risks, for example, which would predictably rise over decades with evidence of higher indoor levels, but not be directly detectable even given a 10-year period of empirical observation).

	Direct empirical data	*Changes in exposure + estimated health impact*
Altered vulnerability to heat-related impacts (improved insulation theoretically protects against heat in most cases, but sometimes may worsen indoor temp. during heat)	• Heat-related mortality • Heat-related hospital admission - both quantified by daily time-series approaches	• Indoor temperatures during periods of heat & cold (>thermal comfort)
Changes relating to adverse effects on the indoor environment:	• Change in hospital admission • Change in mortality (probably insensitive	• Indoor particulate matter levels

e.g. poorer indoor air quality from reduced ventilation (which might exacerbate asthma symptoms, for example)	over the short term) - based on controlled comparison of overall change in cause-specific admissions/death (this is separate from temp-related deaths/admissions)	• Indoor radon, second hand tobacco smoke, mould • Fuel costs
Unexpected adverse impacts	Qualitative study evidence on: • Altered behaviours, budgeting • Unforeseen consequences	-

9.2 Data

9.2.1 Housing and energy efficiency

Data on energy efficiency interventions will be derived from the national HEED data base,[13 14] which records, at individual-dwelling level, HEE interventions (forms of insulation, heating system upgrades, lighting and micro-generation installations) made over the last 15 years or so. Its data are gathered form government scheme (e.g. Warm Front, Energy Efficiency Commitment, Carbon Emissions Reduction Target) management agents and local authorities and other sources. It contains data on over 13 million homes initially held as a double column 'flat file' of approximately 160 million records. The variables in HEED are largely collected using a reduced Standard Assessment Procedure (rdSAP) survey, which provides a 'common data set' level of detail on house characteristics as categorical or nominal variables. It provides evidence on the nature and timing of home energy efficiency interventions carried out through government grant and social sector initiatives, as well as selected privately funded improvements. It provides relatively complete data for areas which have been the focus of targeted campaigns.

9.2.2 Meteorological data

The Met Office will produce the best available dataset of meteorological data to cover the period from 2000 – 2010 for research objective (1). The dataset will include values of hourly air temperature data as well as humidity, from which daily minima maxima and means can be derived, and will be available at postcode district level[15] with the facility to adjust these meteorological parameters towards urban values by areal analysis of weather exposure. The data will be generated using high resolution numerical model 'now-casts'[16] which includes surface, radar and satellite observations, and/or an interpolation of site specific observations. For research objective (2), 35 years of weather observations taken principally at selected UK weather stations will be made available. This dataset will include hourly/daily air temperature values (maxima, minima and means).

9.2.3 Health data

Epidemiological analysis will be based on two health datasets with national coverage, linked to the data on HEED interventions. Each health data set has fine-scale geo-referencing of the individual, using the postcode of residence. The data sets are: (i) national post-coded mortality data, 2000 to 2010; (ii) postcoded hospital episode statistics (HES, England only), 2000/01 to 2009/10.

Each will be linked by day and location to the air pollution and weather data, housing model outputs, small area (Output Area) population data, and regional infectious disease data (Public Health Laboratory Service, Health Protection Agency), using Geographical Information System methods. Linkage can be achieved at fine spatial resolution: the UK postcode relates on average to around 14 households, and the coordinates of most postcode centroids are available to around 10 m accuracy or better; the MINAP data are resolved to around 100m accuracy. In addition we will obtain weekly counts by region of seasonal infectious disease data (influenza and similar) through the Centre for Infection (Public Health Laboratory Service).

9.3 Modelling of indoor environment, energy use & GHG emissions

Building physics modelling will be used alongside analysis of empirical data (1) to improve and simplify the classification of changes in indoor environment (specifically standardized indoor temperature[17]) associated with recorded HEE improvements; and (2) to extend the range of exposures and health impacts assessed beyond those directly measured or where the time-lag for health impact is beyond that of study period (e.g. changes in lung cancer risks from change in radon concentrations where impacts are likely to be deferred for decades) or where the nature of the health impact is uncertain or indirect (e.g. those associated with change in the costs of meeting energy needs, and changes in GHG emissions). This will be led by UCL, extending substantial recent research in this area with LSHTM.

(i) Changes in standardized indoor temperatures The estimation of (group average) changes in standardized indoor temperatures for all dwelling type-intervention combinations will entail: (1) analysis of

existing housing survey data to derive an empirical relationship between standardized indoor temperature and dwelling energy efficiency characteristics (as represented by the dwelling 'E-value'[a] (Watts per Kelvin) of thermal efficiency or similar); (2) categorizing the E-value for each dwelling in the nationally representative sample of 16,000 dwellings in the 2010 English Housing Survey (EHS); and (3) matching dwelling characteristics in the EHS sample with those of the 13 million records in the HEED data, so as to classify both energy efficiency and, from (1), the standardized indoor temperature of each HEED dwelling. Step (1) extends a method described by Oreszczyn et al,[17] and will use data from survey sources with internal temperature monitoring. These include data from the *Warm Front* evaluation, the UCL-led *Carbon Reduction in Buildings (CaRB)* project (EPSRC), the EHS and its predecessor the English House Condition Survey, and selected other field survey data. Indoor temperatures will be 'normalized' by regression methods[17] to standard measurement conditions (mid afternoon temperature on a day with 5 °C day maximum outdoor temperature etc) to yield like-for-like estimates by which dwellings can be classified with regard to the effectiveness of home heating: the *standardized internal temperature* (SIT). How the SIT relates to the physical characteristics of the fabric and heating system efficiency and other relevant parameters (dwelling type, age, household composition etc) will be analysed by a second stage 'meta-analysis' of the SIT data from the various data sets, to provide the temperature classification of HEED dwellings derived in step 3. The *change* in E-values and indoor temperatures associated with HEED interventions will be derived using this method by applying HEED-type efficiency interventions to the EHS variants and linking the results back to the HEED data base. The change in SIT derived in this way reflects both the thermal properties of the dwelling and, importantly, occupant behaviour regarding which determines the degree to which energy efficiency gains are taken as improved winter indoor temperatures rather than as reduced energy costs.

The purpose of these analyses is primarily to provide a means by which different forms of energy efficiency intervention in different types of dwelling can be categorized and ranked using a common currency: the change in standardized indoor temperature. Although it is not possible to be precise about the temperature change of any individual dwelling (because of unknown occupant behaviour etc) the method should provide a reliable classification at group level needed for the epidemiological analysis. Estimates changes in SIT will also be used as inputs to the health impact model of outcomes that are not directly measured. Other parameters that will be quantified include:

(ii) *Indoor air quality* HEED interventions also affect ventilation characteristics of dwellings, which will usually alter concentrations of indoor pollutants (more air-tight dwellings protect against ingress of outdoor particles, but potentially increasing pollutants of indoor origin, including combustion products, carbon monoxide, second hand tobacco smoke, and radon, and alter conditions for mould growth). To quantify changes in these exposures and associated health impacts we will extend an approach used by the applicants[5] based on the application of a validated transient building model (CONTAMW),[18] simulating changes in permeability and associated air pollutant levels for the English stock as reflected by the EHS sample. For mould growth we will use empirical evidence derived from a recent UK study.[19 20]

(iii) *Energy use and heating costs (standardized heating costs and empirical)* Change in energy use and costs with HEED measures will in part be affected by the quality of installation, the behaviour of the occupants in response to the measure (i.e. rebound 'take-back' effect), technical limitations of the system and environmental (weather) conditions. We will quantify the change using a method described by Hamilton et al,[21] which takes into account the empirical temperature take-back effect and the assessed change in E-value. Location-specific climatic data will be used. In addition, further recent work at UCL using the HEED database linked to energy supplier meter data has provided data from which *actual* change in gas demand (the primary source of home heating in the UK) for intervention dwellings can be estimated at aggregate level.

(iv) *Change in GHG emissions* Changes in GHG emissions associated with an efficiency intervention will be estimates using the evidence on energy use by applying benchmark statistics on fuel carbon intensities provided by the Department of Energy and Climate Change (DECC).

(v) *Capital costs of the interventions* (past and future) will also be estimated using existing reference cost data for different forms of intervention.

9.4 Statistical analysis

[a] E-value is the required energy consumption by the principal heating device to maintain a 1°C temperature difference between outside and inside during steady-state conditions ignoring incidental gains/losses.

Objective 1a. Estimation of the overall change in mortality and admission rates that follow an HEE improvement will use. a log-linear Poisson regression model[22] for daily mortality rates conditioning on postcode, in which the parameter of interest (intervention effect) is the coefficient for a variable representing the proportion of residences in that postcode that had by that date received in HEE improvement. Thus, for example, a value of -0.02 for this coefficient would represent a 2% decrease in the outcome rate following an intervention. In further models we will include distinct terms for each type of intervention so as to estimate effect of each separately. Although any one postcode will have very few (sometimes no) outcomes over the observation period, the multiplicity of postcodes overall can support the required estimates.[22] For computational tractability, data will be aggregated over postcodes sharing the same covariates and intervention year and month.

We will control biases by including in the regression model region-specific influenza counts and smooth seasonal and secular trends over time, which will be modelled as natural cubic splines with seven degrees of freedom per year following many time series regression studies.[23] Models for hospital admissions will also include day of week and holiday indicators. As this model conditions on number of outcomes in a postcode over the ten year study period, geographical differences in long-term rates (driven by factors such as SES) do not confound the intervention effect estimates. Nevertheless, to guard against SES predicting trends in outcomes we will allow for variation in trend by additional linear trend terms dependent on IMD of the postcode. Primary analyses will include all postcodes, even those with no intervention, because although they do not contribute directly to the estimated intervention effect, they will contribute to estimating baseline influenza effects and time trends and improve power.

Objective 1b. Estimation of the change in cold and heat-related mortality and admissions following an HEE intervention will follow the same broad conditional Poisson approach, but in this case the focus will be on changes in Poisson regression model coefficients representing impacts on daily mortality of cold and hot weather (variable-coefficient models). As baseline analysis we will use the representation of cold and heat effects as "double-threshold" log-linear models to capture the U-shape temperature-health function, well established in time series literature,[24] and which can reflect the well–known delay of up to three weeks for full cold weather impact to be fully apparent. Here a typical result would be estimated relative risks (RRs) per degree of sub-threshold temperature before and after intervention (say 1.02 and 1.01), and the ratio of these RRs (1.01/1.02=0.99). Sensitivity analyses will relax the linearity assumption both for the outside temperature-health relationship[24] and for the SIT-health relationship.

Objective 2. Estimation of annual cold effects in the 35-year major conurbation series will follow standard time multi-city series approaches but otherwise with control for time-varying risk factors (flu, season, trend) as described above.[23 24] Focus will be on annual (Sept-August) coefficients of linear terms for sub-threshold temperatures ("cold effects"). We will then investigate the relationship between these estimated cold effects and measures of fuel poverty using meta-regression techniques, allowing for a linear improvement over time.

All analyses will be repeated for all-cause and cause-specific mortality, and for all cardiovascular and all respiratory hospital admissions, and separating potentially vulnerable groups (elderly, low SES) in sub-group and interaction models. As further steps to account for potential bias, we will compare HEED data with that from other data sets at the small area level, examine subgroups to understand variations in results with respect to key classifying variables (e.g. data source, housing tenure, intervention type) and perform a range of sensitivity analyses, including limiting analyses to those postcodes with high data coverage and/or with most reliable data (using the HEED 'trust' flag), and using as controls the data only from dwellings that eventually undergo the specific intervention in question.

9.5 Proposed sample size

Adequacy of our available sample size for objectives 1a and 1b indicated by in the table below, which shows estimates of the smallest detectable effect of the intervention, overall (1a) and for response to cold or heat, on a range of outcomes. The very large population covered by the HEED data-base and 11 years study duration implies a very small sampling variability for the overall post-pre (concerns over bias are likely to predominate). Even the more demanding estimation of changes in response to temperature extremes is precise enough to detect realistic changes for cold in all outcomes and for heat (for which the baseline effect is more modest) in the more common outcomes.

Data set	**Total events in HEED (11y)**	**Minimum detectable % reduction after intervention (α=0.05; β=0.2)**	
		Overall[1]	**Response to cold or heat[2]**

Mortality	All cause - Cardio-respiratory	3,300,000 1,800,000	0.3 0.4	1.4 1.9
Hospital admissions	All emergency admissions - Cardio-respiratory - Circulatory disease - Respiratory disease - COPD - Asthma - Bronchiolitis	18,000,000 4,900,000 2,500,000 2,400,000 520,000 420,000 110,000	0.1 0.3 0.4 0.4 0.8 0.9 1.7	0.6 1.2 1.6 1.7 3.6 4.0 7.7

For example, for cardio-respiratory we can detect a post Vs pre intervention reduction of 0.4% overall of 1.9% in the response to cold (eg cold RR changes from 1.100 to 1.081)

1 -- Estimated as $MDRR=100*(1.96+0.84)*\sqrt{(2/n)}$, where n is the number of events to persons over 11 years with residence in the HEED database estimated before or after intervention (time assumed equal on average).

2 -- Cold and heat effects assumed for simplicity in this calculation (planned analyses will use fuller models) to be rates in 5% coldest (hottest) days, relative to the remainder. Typical overall heat and cold effects defined in this way are about 5% and 10% respiratory.[2] $MDRR\%=100*(1.96+0.84)*\sqrt{(1/0.05n+1/0.95n)}$

The control for confounding will diminish power somewhat compared to these crude calculations, but the use of continuous temperatures (objective 1b) will increase it. Detectable reductions in sub-groups will be larger than those in the table following an inverse square root rule: e.g. multipliers of 1.4, 2 and 3.2 for groups of 50, 25 and 10% of the population. For most comparisons, realistic reductions can be found even in small sup-groups. To assess adequacy of sample size for the 35 year conurbation study we make the simplifying assumptions that the association of cardio-respiratory mortality will be compared between the 10 years with greatest and 10 with least fuel poverty, and that the conurbations will include one third of the English population, hence 200,000 deaths a year.[25] With the simplified estimation of response to cold described above (5% coldest days) this leaves 10,000 cold-exposed deaths a year, hence 100,000 in each (fuel poor or not) group of years. Ignoring uncertainty from the baseline (95% days not "cold") this give a standard error of the ratio of cold response (RR) in the two groups of $\sqrt{(2/100,000)} = 0.4\%$. Thus a minimum detectable increase in cold response in the years with greatest fuel poverty of $(1.96+0.84)*0.4=1.1\%$. Set against a baseline cold response of 10%, this seems realistic.

10 Multi-criterion decision analysis (MCDA)

The Multi-Criteria Decision Analysis (MCDA, see appendix 2) is well recognized at governmental levels as a modelling tool to support policy makers make robust decisions.[26] The MCDA model will use approaches currently being developed by the applicants. It will take input from the main study results (for cold-related mortality and hospital admission), as well as a *health impact model*, which will include assessment of outcomes that are not directly measured, but whose impacts will be quantified based on assessed changes in exposures (from the building physics models etc). Some of these pathways are outlined in Appendix 3. The methods will broadly follow those previously applied by the applicants for the *Task Force on Climate Change Mitigation and Public Health*,[5] using an approach akin to that taken by the WHO for the Comparative Risk Assessment exercise. The model will also enable the evidence on the effect of fuel pricing and cold weather payments to be integrated with other results.

The MCDA model will be used to examine alternative intervention options across a number of criteria including costs (of the intervention and to the NHS), and from the perspective of different policy makers (e.g. DECC, DCLG, NHS) and user groups (voluntary sector). The evidence on impacts and costs generated in the different phases of the project will be used to inform the MCDA modelling framework. It will be applied to assess: (i) the range of health impacts of past HEE interventions (to 2010), and (ii) a range of policy options for the future. A key component of the MCDA is addressing the uncertainty in the evidence and its impact on decision-making. Value of information analysis (VOI) will also be used to determine the contribution of what further evidence is required to resolve the uncertainty in the decisions.[27 28 29] Workshops with stakeholders will be held at the inception of the project to inform details of the analytical design, and towards the end to help evaluate how its evidence alters policy choices. These will also be an important vehicle of dissemination.

11 Qualitative study

The study's qualitative element will contribute to our understanding of the pathways linking home energy efficiency (HEEs) improvements and cold-related morbidity and mortality, and to identifying implications for future interventions that aim to increase uptake of HEE interventions. The aims are to:

(a) Further our understanding of the pathways and mechanisms that link implementation of HEE interventions and social practices related to the determinations of health;

(b) Identify how these pathways may change over time post-installation;

(c) Further our understanding of the factors that facilitate and inhibit the uptake of HEE interventions across different population groups and different points in household lifecycle;

(d) Identify the implications of household decision making for future policy implementation.

Previous research has suggested that key pathways linking home energy efficiency interventions and health are likely to include: direct physiological effects of higher indoor temperatures or reduced humidity; social and psychological effects of greater emotional security (which might indirectly impact on physical health); reduced fuel poverty from lower fuel bills. There have been calls for more research on the processes which, for instance, mental health gains from increased temperatures might influence physical health outcomes. There are also gaps in the literature on how salient these pathways are across different population groups (eg through the lifecourse) and how far preferences for (for instance) open windows, colder indoor temperatures, or reducing fuel use are rooted in personal circumstances or more deeply seated beliefs relating to health or climate change. Given that more radical interventions to improve household efficiency will be needed to meet GHG reduction goals, a more nuanced understanding of the motivations and barriers to household uptake and use of HEE interventions is urgently needed.

To both further our understanding of the pathways by which HEE interventions impact on health and to identify factors likely to shape future uptake, we aim to explore the effect of past interventions on households and to identify the key factors framing their approach to future interventions. To do this, the qualitative component of this study aims to explore how home energy practices are integrated into everyday household decisions across a range of household types. Using individual and household interviews with 50 households purposively sampled across four geographical regions and at different points post-HEE installation, we will explore: decisions to implement HEE (or not); changes to household practices over time post-HEE installation; underlying values and beliefs relating to domains such as indoor temperature, ventilation, fuel use and responsibilities for climate change.

Home Energy Efficiency (HEE) interventions relate to a number of major policy concerns. First, the National Cold Weather Plan for England[10] identifies interventions such as home insulation as key to long term planning to reduce excess winter mortality. Second, reducing fuel consumption at the household level is a consideration for climate change mitigation. Third, the targeting of subsidised HEE interventions at those in poor housing and on low income has also been a strategy for addressing fuel poverty and the associated health impacts.[11 30] However, at the household level, motivations for installing HEE interventions may be differently framed, with incentives such as reducing fuel bills, improving property values, or aesthetics.[31] The premise of the qualitative element is that to understand the impact of HEE interventions on health and to inform future policy implementation across these agenda, we need to understand the adoption, use and incorporation of HEE interventions as *social practice*. That is, we aim to explore the impact of HEE intervention (or the decision not to install any HEE intervention) technologies as part of the broader practices and decision-making of a household.

This study builds on the considerable body of research already conducted on home energy improvements and on cold weather related behaviour, particularly in older citizens (see eg Gilberston et al 2006,[32] Critchley et al 2007,[33] Hitchings & Day 2011[34]). In summary, reviews of evidence on interventions to address fuel poverty suggest that: there have been measurable impacts on perceived wellbeing and mental health, but that clinical changes are difficult to identify, in part because past evaluations have not been powered to detect these;[12] that targeted interventions could address inequalities[35] and most studies to date have looked at short term outcomes.[35] Although the strongest evidence for health effects have related to perceived well being, this should not be underestimated: detailed qualitative research as part of the *Warm Front* Scheme evaluation[32] documented significant benefits from the improvements in quality of life, arising from increased comfort and use of living space within homes. Increases in emotional security from reliable, warmer homes were linked to increases in wellbeing, with improvements in the use of living space, comfort and household relations. As Liddell & Morris[12] note, such mental health effects may be a key mechanism for reported gains in physical health: they conclude more research on process is needed.

One aspect of process is the effect of HEE interventions on indoor temperature, given that households can prioritise either increasing temperature or reducing fuel costs. In contrast to the Warm Front evaluation, which found temperature gains but relatively little impact on fuel bills,[32] a New Zealand study[36] found modest changes in indoor temperature, but significantly reduced fuel bills post-intervention. The health gains observed, they suggest, may therefore be due to reduced exposure to very low cold or high humidity, rather than higher average temperatures. Gains from higher disposable income may also, of course, have an effect on household health. Day and Hitchings[37] found that heating was the last thing that older householders would compromise on in terms of sustainability, but it is not known how far such trade-offs between sustainability and comfort might be affected by future changes in householders' attitudes to sustainability, or in younger cohorts.

The decision about whether to prioritise fuel use reduction or temperature increases is one example of the variable responses possible to HEE improvements in the household. Previous research identifies a range of response to HEE interventions, and to advice on cold-weather related health in general, but has not (to date) gone much beyond noting that there are differences. Harrington et al[38] for instance, identified a range of views in households in the Warm Homes Project, and a range of coping strategies used by older citizens, but only suggested that these were likely to be cultural and historically specific. Psychological factors are also likely to modify pathways. Critchley et al[33] looked specifically at those households which maintained cold temperatures post installation of heating improvement interventions, distinguishing those who preferred such temperatures, and those for whom constraints had limited temperature increases: cold, they suggest, may well have different health effects for those who psychologically adapt to or prefer colder temperatures than those who perceive little choice over their indoor temperatures. If we take seriously the issue of comfortable temperature being a subjective measure, then feelings of control over it are likely to be as important as objective temperature in the pathways linking HEEs and health. This suggests potentially complex pathways linking HEE improvements and health, with possible feedback mechanisms as (for instance) cultural norms relating to 'normal' indoor temperature rise. One map of possible pathways linking HEE interventions and health is proposed by Liddell and Morris,[12] covering perceived impacts on health. More work is needed to unpack not only other potential pathways, but also to identify social and cultural factors that might be included and which might modify these pathways.

Feelings of control, as well as social practices that affect cold weather and fuel related practices, are likely to shift across the life course. Exploring how older households managed 'thermal comfort', Day and Hitchings[34] identified several ways in which ageing related to cold weather practices. First, ageing was perceived as a factor in growing sensitivity to cold, but also a barrier to various potential strategies for keeping warm, given the potential stigma of obvious signs of an 'ageing body', such as using a blanket indoors or a hat to sleep in. Windows were often opened to allow fresh air to maintain mental alertness and to guard against discreditable 'stuff' smells. They note ventilation practices are under-explored in general.[34] To date, little is known about how far these are personal preferences, or more deeply rooted in cultural beliefs about the necessity for 'fresh' air, and therefore how malleable they are. In their study of winter warmth practices in older citizens, Hitchings and Day[39] found that although social networks were an important part of how people found out about, for instance, strategies for keeping warm, that they knew very little about what was 'normal' for their age cohort, and indeed did not identify with any wider collective of 'older people'.

A number of gaps in the emerging body of literature on HEE are thus relevant to the question of how HEE improvements impact on health. First, we need more detail about mechanisms on the likely causal pathways between HEE improvement and health related practices. Second, we need a more nuanced understanding of attitudes to and practices related to indoor temperatures and fuel use. For instance: are they culturally framed, do they vary across social groups, to what extent are they malleable, and how far do they change through the life-course, or as a result of HEE improvements? Third, to inform future policy development, following from EST (EST undated) research on 'triggers' to adopting HEE improvement, we need more on how policy imperatives and wider social changes (eg rising fuel prices) impact on household level social practices relating to HEE improvements.

11.1 Sampling and data generation and analysis

This study will use qualitative interviews to maximise the opportunities to explore in depth how reactions to and decisions about HEE improvements are made in practice, given that we know attitudes or reported behaviours identified in surveys may not reflect the complexities of how decisions are taken in everyday life. By focusing on households, we aim to generate detailed narratives and exchanges on the range of social practices relating to both how existing HEE improvements have affected the household, and how future decisions might be taken. Recall of past events (up to several years after improvements) should not be a major source of bias as the primary focus is to generate accounts and discussion of events of decision making and reactions to HEE at various points after installation. The design involves 50 interviews with individual householders in three regions, followed (where possible) by interviews with the whole household.

<u>Sample</u> The aim of the sampling strategy is to generate enough data to provide analytical comparisons across the following factors theoretically (based on above literature) likely to be linked to social practices: local norms about HEE interventions (indicated by high/low density of take up); HEE adopted and length of

time since adoption (no installation/one year post/3 years post); household type (working age no children/family with young children/older citizens); area deprivation; geographical region (including north/south east rural, suburban and urban locations); those with the more extensive HEE upgrades likely to be necessary in the future. Dwellings that have received levels of intervention more typical of the more extensive forms of HEE upgrade that are expected in future will be targeted. A sampling grid will be used to select around 50 households across three regions. Within each region, we will choose two small localities, one with high take up one with low, and within that sample households to ensure a range of other variables across the sample. The aim will be to sample to analytical saturation: we estimate that this will require around 50 households. The sampling strategy does not aim to generate a statistically representative sample, but rather a sample with enough variation across the factors likely to affect experiences of the intervention to allow internal comparisons. Although this a volunteer sample, and we are therefore less likely to access the views of the more mobile householders, or perhaps those with fewer strong views about the intervention, we will compare demographic characteristics with those not volunteering to provide some purchase on likely biases.

Recruitment Households will be recruited by invitations to participate mailed with an SAE to addresses covered by the Home Energy Efficiency database, selected as above. Where possible, we will interview both the householder, and (at a repeat visit) the whole household in a natural group interview, in order to generate data on both the potentially more private issues (eg impact on fuel bills) as well the data on social practices, which may be more feasible to generate in natural group interviews.

Data generation and analysis Pilot interviews will refine topic guides for in depth interviews with a) the householder and b) the whole household. These are likely to cover: experience of applying for and organising the interventions; narratives of how life in the home was before/immediately after/now the intervention; impact on physical and mental health; impact on fuel costs; comparisons with neighbours/family members in similar homes without energy interventions; views of the importance of energy efficiency interventions compared with other potential benefits to improve health and wellbeing. These topics will not generate direct answers to our research questions, but analysis will identify underlying framings for decisions and attitudes to the domains of interest. All early interviews and selected later ones will be transcribed in full, and analysed qualitatively, using techniques from the constant comparative method[40] for inductive analysis as well as a more deductive content analysis around 1)key themes of interest related to wellbeing and 2) the relative importance users put on these interventions in the context of health, wellbeing, costs and climate change. Nvivo will be used to manage the data and facilitate discussion of coding frameworks by JG, the researcher and wider team.

12 Ethical arrangements

The main ethics issues relate to the handling of postcode health data (issues of confidentiality and security) and the qualitative interviews. We will work with ONS who will provide the secure data linkage via their facility at Titchfield. Interview participants will provide consent to their interviews being audio-recorded for analysis, assured of confidentiality and offered a summary of the findings. All transcripts will be anonymised, with any identifying details removed. Audio-recordings and transcripts are kept securely. Ethics approval will be requested from LSHTM ethics committee, the National Research Ethics Service for the handling of mortality and hospital admissions data, and the Health Research Authority Confidentiality Advisory Group (CAG).

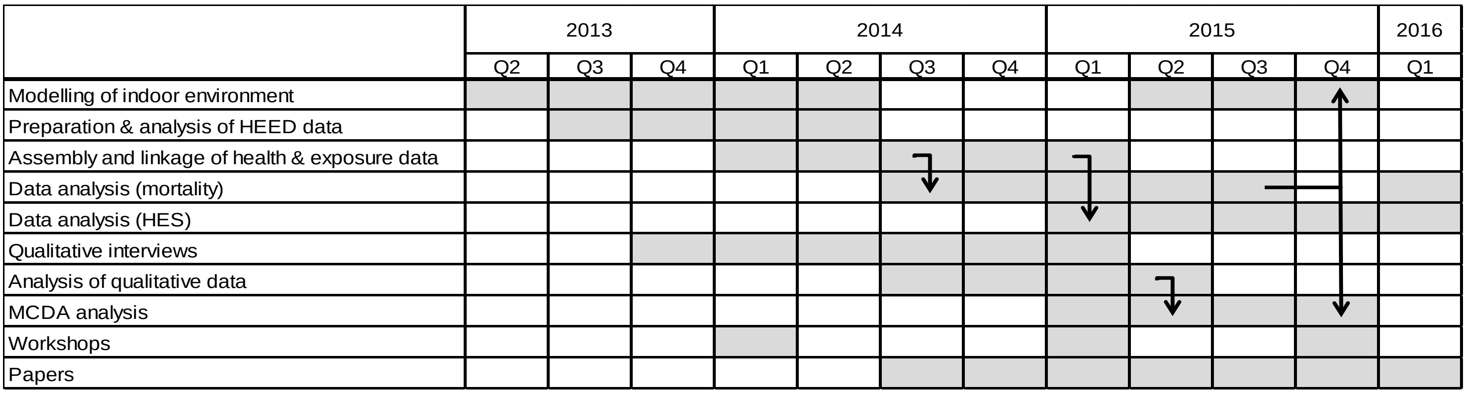
13 Research Governance and partner involvement

The research will be carried out in accordance with usual research governance practices for public health research of this nature, and in line published policies by LSHTM and partner organizations. The project will be overseen by a Knowledge Transfer Steering Group, led by Dr James Goodwin who chairs and pioneered the concept with the Halcyon NDA project and who is the deputy chair of a World Health Organization Knowledge Transfer group. We will engage a wide variety of other stakeholder groups throughout: at the inception of the project to help shape details and focus of its analytical design; subsequently to exchange emerging results; and in later stages to assist with interpretation of policy implications and dissemination. It will draw membership from both academic and policy communities, including representation of key users and the public. The project principal investigator and collaborators have extensive experience of running large evaluation projects of this kind, and will ensure best practices are followed in all elements of design, conduct and dissemination.

We plan to use an innovative model of knowledge transfer (KT) to engage with users and to achieve our aim of fully involving our project partners. The innovation derives from our over-arching concept of interacting with our major stakeholders throughout the project, rather than working in isolation from them. In addition to the two academic partners (LSHTM and UCL), the main project team includes several non-academic collaborators who are intrinsic to all phases of the research (design, data gathering/processing, analysis, interpretation, assessment of policy implications, dissemination, policy-to-practice). They are Department of Health (the project teams includes the lead for the cold weather plan for England), the Energy Saving Trust (responsible for advising on many aspects of housing energy efficiency in England, and the curator of the Home Energy Efficiency Database (HEED) on which the project will be based); the Met Office (who have unrivalled expertise in the use of weather data) and AgeUK (who represent a key target group for policies and actions). Specifically, we propose to engage stakeholders from the voluntary sector (e.g. AgeUK, housing charities, TransformUK); key government departments (especially the Department of Energy and Climate Change, the Department of Communities & Local Government and the Department of Health – with all of whom we have established links regarding the health impacts of home energy efficiency); the Greater London Authority (GLA); representatives of the NHS and of the Health Protection Agency (Public Health England); with the National Housing Federation; BRE; as well as the private sector (energy and construction companies); government scheme managing agents, and with householder/tenant groups, and the World Health Organization (WHO).

14 Project timetable and milestones

3 years from Apr 2013



Key milestones will include: completion of main components of a model of health impact model (relating to changes in the indoor environment) by Mar 2014, with later further refinements from the input of the results of the quantitative analyses; development and implementation of the methods for data linkage for mortality, including prepared explanatory data, by Sept 2014; completion of interviews by Mar 2015, and their analysis and writing up by end June 2015; completion of main epidemiological analyses for mortality by Sep 2015 and HES by Dec 2015; implementation of the MCDA by Dec 2015. Papers will form outputs from the third quarter of 2014, and workshops for stakeholders engagement will be annual.

15 Expertise

The research team is multi-disciplinary, bringing together expertise in epidemiology, statistics, meteorology, building science,social science methods, large database analysis, and health economics/decisions analysis, and has collaborators from both the academic and policy sectors.

(LSHTM) Prof Wilkinson (PI) has extensive research expertise in temperature (weather)-related impacts on health, in housing and health, as well as in the methods for the evaluation of public health interventions. He has coordinated numerous relevant major collaborative research projects. Prof Armstrong is a statistician and epidemiologist with an international reputation for research into weather-related health impacts, and extensive expertise in analytical methods, which have been developed in particular through recent MRC-funded methodological projects. Dr Chalabi, senior lecturer in mathematical modelling, has led the development of the methods and the mathematical framework for multi-criterion decision analysis of environmental interventions through such projects as IntraWise, AWESOME, PURGE listed below. Judith Green, Reader in Sociology of Health, has expertise in qualitative methodologies for public health research, and an extensive track record of relevant research, and on research evidence and policy.

(DH) Professor Doyle, Regional Director of Public Health for the South East, has primary responsibility within the Department of Health for the Cold Weather Plan for England, and winter-related burdens, and has intimate knowldege of the policy needs and opportunities, as well as of the roles of key actors.

(Energy Saving Trust). Andy Deacon represents the Energy Saving Trust and the team responsible for assembling and analysing the Home Energy Efficiency Database (HEED), which is critical to the characterization of dwelling-related evidence on the timing of home energy efficiency interventions.

(Loughborough University and Research Director for Age UK). James Goodwin has a long track record of research in the impacts of temperature on health, and will coordinate stakeholder involvement.

(Met Office) Patrick Sachon and team bring expertise in the use of meteorological data. They have been responsible for establishing and assessing the Met Office weather-based warning scheme for COPD.

(UCL) Prof Davies, Professor of Buildings and Environment at UCL, is a leading expert in the performance of buildings and the modelling of indoor environments. He has extensive relevant research experience.

16 Members of the Public

This project has most relevance for elderly people living at home. We intend to engage with members of the public through AgeUK, with their participation in the Knowledge Transfer Steering Group and through project workshops and other engagement activities, coordinated by AgeUK (which has exceptional expertise and experience within the UK of knowledge translation and an extrensive apparatus for public engagement and dissemination) as described in section 13.

17 References

1. Wilkinson P, Pattenden S, Armstrong B, Fletcher A, Kovats RS, Mangtani P, et al. Vulnerability to winter mortality in elderly people in Britain: population based study. BMJ. 2004 Sep 18;329(7467):647.
2. Hajat S, Kovats RS, Lachowycz K. Heat-related and cold-related deaths in England and Wales: who is at risk? Occup Environ Med. 2007 Feb;64(2):93-100.
3. Wilkinson P, Landon M, Armstrong B, Stevenson S, McKee M. Cold comfort: the social and environmental determinants of excess winter death in England, 1986-1996. York: Joseph Rowntree Foundation; 2001.
4. Jackson G, Thornley S, Woolston J, Papa D, Bernacchi A, Moore T. Reduced acute hospitalisation with the healthy housing programme. J Epidemiol Community Health. 2011 Jul;65(7):588-93.
5. Wilkinson P, Smith KR, Davies M, Adair H, Armstrong BG, Barrett M, et al. Public health benefits of strategies to reduce greenhouse-gas emissions: household energy. Lancet. 2009 Dec 5;374(9705):1917-29.
6. Osman LM, Ayres JG, Garden C, Reglitz K, Lyon J, Douglas JG, et al. The effect of energy efficiency improvement on health status of COPD patients. A Report to the Eaga Partnership Charitable Trust. Newcastle, UK: EAGA Chartiable Trust; 2007.
7. Osman LM, Ayres JG, Garden C, Reglitz K, Lyon J, Douglas JG. A randomised trial of home energy efficiency improvement in the homes of elderly COPD patients. Eur Respir J. 2010 Feb;35(2):303-9.
8. Howden-Chapman P. Housing and inequalities in health. J Epidemiol Community Health. 2002 Sep;56(9):645-6.
9. MRC. Using natural experiments to evaluate population health interventions. Report of a joint MRC Population Health Sciences Research Network/MRC Methodology Research Panel Workshop. London: MRC; 21 January 2010.
10. Department of Health. Cold weather plan for England: protecting health and reducing harm from severe cold weather. London: Department of Health; 2011.
11. Hills J. Fuel Poverty: The problem and its measurement. CASE Report 69. London: LSE for the Department of Energy and Climate Change; 2011 19 October 2011.
12. Liddell C, Morris C. Fuel poverty and human health: a review of recent evideence. Energy Policy. 2010;38:2987-97.
13. Department of Energy and Climate Change. National energy efficiency data framework. Report on the development of the framework and initial analysis. London: DECC; 2011 June 2011.
14. Hamilton I, Steadman J, Lowe R, Bruhns H, Summerfield A. Buildings and Energy Data Framework: Report on the exploratory analysis of the Homes Energy Efficiency Database and Energy Demand. London, UK: University College London; 2011.
15. Moseley S. From observations to forecasts - part 12: getting the most out of model data. Weather. 2011;66(10):272-6.
16. Rawlins F, Ballard S, Bovis K, Clayton A, Li D, Inverarity G, et al. The Met Office global four-dimensional variational data assimilation scheme Quarterly Journal of the Royal Meteorological Society. 2007;133(623):347-62.
17. Oreszczyn T, Wilkinson P, Sung H, Ridley I, Group. ftWFS. Determinants of winter indoor temperatures in low income households in England. Energy & Buildings 2006;38(3):245-52.
18. Dols W, Walton G. Multizone Airflow and Contaminant Transport Analysis Software (CONTAMW). Washington: National Institutes of Standards and Technology (NISTIR), Technology Administration, US Department of Commerce; 2002.

19. Oreszczyn T, Ridley I, Hong S, Wilkinson P. Mould and winter indoor relative humidity in low income households in England. Indoor built environment. 2006;15(2):125-35.
20. Oreszczyn T HS, Ridley I, Wilkinson P, for the Warm Front Study Group. . Determinants of winter indoor temperatures in low income households in England. . Energy & Buildings 2006 March 2006;38(3):245-52.
21. Hamilton I, Davies M, Ridley I, Oreszczyn T, Barrett M, Lowe R, et al. The impact of housing energy efficiency improvements on reduced exposure to cold - the “temperature take back factor.”. Build Ser Engineer Res Tech. 2011 1 Feb 2011;32(1):85-98.
22. Grundy C, Steinbach R, Edwards P, Green J, Armstrong B, Wilkinson P. Effect of 20 mph traffic speed zones on road injuries in London, 1986-2006: controlled interrupted time series analysis. BMJ. 2009;339:b4469.
23. Dominici F, Samet J, Zeger SL. Combining evidence on air pollution and daily mortality from the 20 largest cities: a hierarchical modelling strategy. J Roy Stat Soc A. 2000;163:663-302.
24. Armstrong B. Models for the relationship between ambient temperature and daily mortality. Epidemiology. 2006 Nov;17(6):624-31.
25. Pattenden S, Armstrong B, Milojevic A, Heal MR, Chalabi Z, Doherty R, et al. Ozone, heat and mortality: acute effects in 15 British conurbations. Occup Environ Med. 2010 Oct;67(10):699-707.
26. DCLG. Multi-criteria analysis: a manual. . London: Department for Communities and Local Government; 2009.
27. Chalabi Z, Epstein D, McKenna C, Claxton K. Uncertainty and value of information when allocating resources within and between healthcare programmes. European Journal of Operational Research 2008;191:529-38.
28. McKenna C, Chalabi Z, Epstein D, Claxton K. Budgetary policies and available actions: a generalisation of decision rules for allocation and research decisions. J Health Econ. 2010 Jan;29(1):170-81.
29. Petticrew M, Chalabi Z, Jones D. To RCT or not to RCT: deciding when ‘more evidence is needed’ for public health policy and practice. Journal of Epidemiology and Community Health. 2011.
30. Marmot Review Team. The Health Impacts of Cold Homes and Fuel Poverty. London: Friends of the Earth & the Marmot Review Team; 2011.
31. Energy Saving Trust (EST). Trigger points: a convenient truth: promoting energy efficiency in the home. London: EST; (undated).
32. Gilbertson J, Stevens M, Stiell B, Thorogood N. Home is where the hearth is: grant recipients' views of England's home energy efficiency scheme (Warm Front). Soc Sci Med. 2006 Aug;63(4):946-56.
33. Critchley R, Gilbertson J, Grimsley M, Green G, and the Warm Front Study Group. Kiving in cold homes after heating improvements: evidence from Warm Front, England's home energy efficiency scheme. Applied Energy. 2006;84:147-58.
34. Day R, Hitchings R. 'Only old ladies would do that': age stigma and older people's strategies for dealing with winter cold. Health Place. 2011 Jul;17(4):885-94.
35. Thomson H, Thomas S, Sellstrom E, Petticrew M. The health impacts of housing improvement: a systematic review of intervention studies from 1887 to 2007. Am J Public Health. 2009 Nov;99 Suppl 3:S681-92.
36. Howden-Chapman P, Matheson A, Crane J, Viggers H, Cunningham M, Blakely T, et al. Effect of insulating existing houses on health inequality: cluster randomised study in the community. BMJ. 2007 Mar 3;334(7591):460.
37. Day R, Hitchings R. Older people and their winter warmth behaviours: understanding the contextual dynamics. Report for Nuffield Foundation. Birmingham: University of Birmigham/UCL; 2009.
38. Harrington BE, Heyman B, Merleau-Ponty N, Stockton H, Ritchie N, Heyman A. Keeping warm and staying well: findings from the qualitative arm of the Warm Homes Project. Health Soc Care Community. 2005 May;13(3):259-67.
39. Hitchings R, Day R. How older people relate to the private winter warmth practicews of their peers and why we should be interested. Environment and Planning. 2011;43(10):2452-67.
40. Glaser A. Qualitative analysis for social scientists Cambridge CUP; 1987.