Health and Climate Change 1

Public health benefits of strategies to reduce greenhouse-gas emissions: household energy

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Energy used in dwellings is an important target for actions to avert climate change. Properly designed and implemented, such actions could have major co-benefits for public health. To investigate, we examined the effect of hypothetical strategies to improve energy efficiency in UK housing stock and to introduce 150 million low-emission household cookstoves in India. Methods similar to those of WHO's Comparative Risk Assessment exercise were applied to assess the effect on health that changes in the indoor environment could have. For UK housing, the magnitude and even direction of the changes in health depended on details of the intervention, but interventions were generally beneficial for health. For a strategy of combined fabric, ventilation, fuel switching, and behavioural changes, we estimated 850 fewer disability-adjusted life-years (DALYs), and a saving of 0·6 megatonnes of carbon dioxide (CO_2), per million population in 1 year (on the basis of calculations comparing the health of the 2010 population with and without the specified outcome measures). The cookstove programme in India showed substantial benefits for acute lower respiratory infection in children, chronic obstructive pulmonary disease, and ischaemic heart disease. Calculated on a similar basis to the UK case study, the avoided burden of these outcomes was estimated to be 12 500 fewer DALYs and a saving of 0·1–0·2 megatonnes CO_2-equivalent per million population in 1 year, mostly in short-lived greenhouse pollutants. Household energy interventions have potential for important co-benefits in pursuit of health and climate goals.

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Introduction

Climate change presents a formidable challenge to societies throughout the world.[1–3] Targets to limit the global temperature rise to around 2°C and the risk of dangerous climate change to a low level present a very challenging abatement path, needing a worldwide peak in greenhouse-gas emissions within only a few years and a steep fall that would halve emissions by around 2050.[4] Even this target might be insufficiently ambitious. We employ the widely used term greenhouse gases, although since some anthropogenic climate-active atmospheric species are aerosols, greenhouse pollutants is a more accurate term. Most important of the climate-active aerosols produced by human activities are black carbon, sulphate, and organic carbon particles, which have important although not identical health effects, but quite different climate implications.[5]

Key messages

- Many important health and climate outcomes are related to the products of incomplete combustion that are emitted from traditional solid fuel use in developing countries, even when little carbon dioxide (CO_2) is produced overall.
- Sustained national programmes to promote modern low-emissions stove technology for burning of local biomass fuels in poor countries provide a highly cost-beneficial means to potentially avert millions of premature deaths and hundreds of millions of tonnes of CO_2-equivalent greenhouse pollutants. Such programmes could help countries to achieve Millennium Development Goals and climate targets, and offer one of the strongest climate–health links with respect to co-benefits.
- Improvements in the efficiency of UK household energy use could, if implemented correctly, have appreciable benefits for population health, mainly arising from improved indoor air quality and control of winter indoor temperatures.

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- For UK housing interventions, the magnitude and even direction of effects on health depend on how energy efficiency measures are implemented and maintained. Potential for adverse health outcomes arises from increases in indoor concentrations of pollutants, including radon and environmental tobacco smoke, in dwellings with energy efficiency measures that reduce air exchange; and increased ingress of outdoor particle pollutants with higher air exchange rates in dwellings fitted with mechanical ventilation systems unless there is effective filtering of air.
- Household energy interventions in low-income settings have greater potential to improve public health than do those in high-income countries, but household energy interventions in high-income settings have potential for greenhouse-gas reduction per dwelling and are vital for achievement of climate abatement targets worldwide.

Urgent and profound changes in power generation and energy use in all sectors are therefore necessary, especially in high-income countries, where a halving of emissions is needed by 2030.[4,6] Action to reduce energy use by households and in buildings is especially important because of the scale of their contribution to greenhouse-gas emissions and the opportunities for emissions reduction. Currently, energy use in UK residential buildings is estimated to account for around 140 megatonnes of carbon dioxide (CO_2) emissions,[4,7] or around 26% of the country's total (table 1). Substantial reductions in these emissions are achievable with present technology and through energy efficiency, behavioural change, and low-carbon power generation.[4]

In low-income countries, where per head emissions are low, global principles of equitable burden sharing imply that less contraction in greenhouse-gas emissions is necessary compared with high-income countries, and even, in some cases, an increase to a sustainable per head worldwide average. But even in such settings, efficiency and cleanliness of household energy use can be improved, with both greenhouse-pollutant reductions and direct health benefits from reduced indoor and outdoor air pollution. Improvement of combustion efficiency of solid household fuels (biomass and coal) used by poor populations of developing countries is one of the greatest opportunities for health co-benefits worldwide and was among the first to be recognised.[8] The poorest half of the world's households rely on such fuels, with the highest fraction of households in sub-Saharan Africa, followed by low-income Asia (figure 1).[9,10]

Most of this combustion is done in simple stoves with low combustion efficiency, thus producing large amounts of products of incomplete combustion,[5] with consequences for both climate and health. When biomass is harvested renewably—eg, from standing tree stocks or agricultural wastes (crop residues and animal dung)—no contribution to atmospheric CO_2 is made. Net CO_2 is produced, however, when harvesting of wood fuels leads to deforestation. In detail, such determinations are difficult and depend on local, sometimes changing, conditions. Therefore, we do not assume any CO_2 reductions. Because the products of incomplete combustion include important short-lived greenhouse pollutants, however, even sustainable harvesting does not make such fuel cycles greenhouse neutral.[5]

	Total for all sectors (megatonnes per year)	Housing sector (megatonnes per year)	
		Sector total	Total (adjusted)*
1990†	593	156	154
2010†	542	142	140
2030‡	297	78	77

*Emissions exclude non-aerosol consumer products as per National Atmospheric Emissions Inventory.[7] †Data for 1990 and 2010 total emissions are from reference 7. 2010 emissions assumed to be the same as 2007 emissions. ‡2030 emissions are estimates based on 50% reduction for all sectors from 1990.

Table 1: **UK total and housing sector carbon dioxide emissions in 1990, 2010, and 2030**

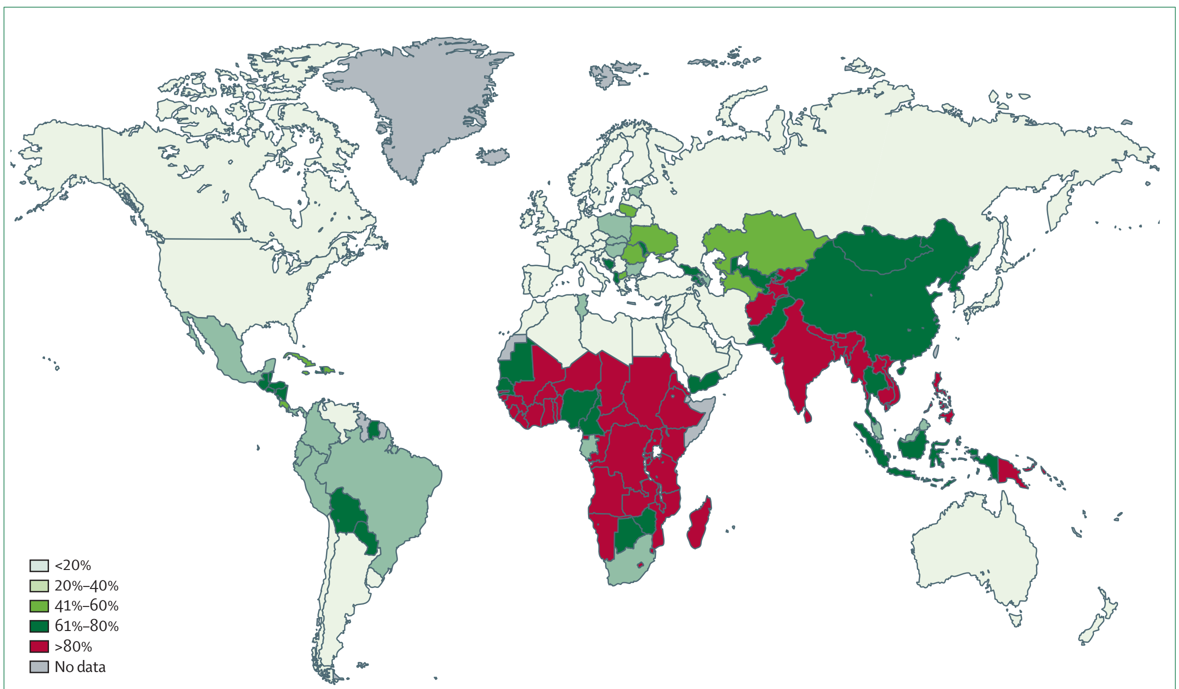

***Figure 1:* National use of solid fuels for cooking in 2000**
Solid fuel is mostly in the form of biomass (wood and agricultural residues), even in China, where many households use coal. Data are from reference 10.

Case studies

We considered case studies in two countries—the UK and India—as examples of high and low per head CO_2 emissions. The International Energy Annual[11] shows that, in 2006, emissions of CO_2 from the consumption and flaring of fossil fuels were 9·66 metric tonnes per head in the UK and 1·16 tonnes per head in India. These figures rank the UK 49th highest worldwide in terms of per head emissions of 206 countries with 2006 emissions data (15th highest of 35 European countries), and India as 137th highest (25th of 42 countries in Asia, Australasia, and Pacific Islands). For each country we chose household-energy efficiency interventions of the types that are most relevant to policy needs and have a bearing on health.

For the UK, we specified interventions to improve the energy efficiency of heating of the housing stock through changes to the dwelling fabric (ie, to the thermal properties of the materials of the walls, windows, floor, and roof), ventilation control, fuel use, and occupant behaviour. At present, space heating is estimated to account for 53% of household CO_2 emissions (74 megatonnes of CO_2).[12] Panel 1 details the five specific scenarios. These scenarios explore interventions based on present technology of the type and scale needed to meet 2030 abatement targets, as described by the UK Climate Change Committee.[4] The interventions can be viewed as examples of actions that will need to be implemented in many other industrialised countries. The costs associated with these interventions are described in the webappendix p 28, but because of the complexity we did not attempt to quantify costs in detail. The broad range is a one-off cost of US$5000–50 000 per dwelling, offset by reduced yearly fuel bills of around $500 per year at estimated 2010 prices.

For India, we specified a 10-year programme to introduce 150 million low-emissions household cookstoves. This scenario was chosen because of the major public health burden that is associated with indoor air pollution from inefficient burning of biomass fuels in India and in many other low-income countries. It is also consistent with proposals that are being considered in India. The cost would be less than $50 every 5 years, perhaps paid partly through government subsidy and partly by the households because of fuel cost savings and time savings in harvesting of fuel.

The scenario used here draws lessons from the previous Indian national stove programme, the National Programme for Improved Chullhas,[13] which, like the major national programme in China,[14] was initiated in the early 1980s and focused mainly on increasing fuel efficiency to assist with rural welfare and, to a lesser extent, protect forests. Secondary emphasis was on reduction of smoke exposure through use of chimneys, and there was no consideration of outdoor pollution or climate. However, there have been major changes in our understanding about the value of and technology for emissions reductions and in world conditions that have modified the landscape for improved biomass stove programmes.

The changes in health related to traditional fuel use patterns are much better established than they were previously, with hundreds of reports documenting the associated health outcomes. An estimated 400 000 premature deaths per year in India are caused by biomass-fuel use in households.[9] The international price of liquified petroleum gas, which is the major alternative clean household fuel, will probably continue to increase faster than will rural incomes, making the transition to modern fuels difficult and, if subsidised by government,

Panel 1: Exposures and associated changes in health included in models of mitigation measures applied to UK housing stock

Baseline (2010)
Distributions of efficiency for UK housing stock (ie, fabric, ventilation) and associated greenhouse-gas emissions and health effects.

Scenario 1: fabric improvements
Overall heat loss of the fabric is reduced (from 224 J/s per °C to 98 J/s per °C) because of increased insulation, reducing exposure to wintertime cold.

Scenario 2: improved ventilation control
Air tightness and ventilation systems are improved. The present permeability of the housing stock is shifted to represent reduced air leakage in all dwellings. Those dwellings in the tightest band (3 m^3/m^2 per h), in addition to the shift, have (idealised) mechanical ventilation and heat recovery systems installed.

Scenario 3: fuel switching
All indoor household fossil fuel (eg, gas, coal, oil) combustion sources are removed and switched to electricity without change to ventilation characteristics. The effects on health are modelled, but those on carbon dioxide (CO_2) emissions are not. Currently, such a shift would increase CO_2 emissions because of the CO_2 content of electricity, but this is projected to decrease rapidly to 2030 and beyond. We make the assumption that the opportunity is taken during refurbishment to fit high capture efficiency hoods to all cookstoves.

Scenario 4: occupant behaviour
Dwellings with internal average temperatures greater than 18°C are reduced by 1°C by occupants to an upper limit of 18°C. Temperatures less than 18°C are unchanged.

Scenario 5: combination of scenarios 1–4
Fabric insulation is increased along with an overall improvement in ventilation and air tightness (ie, scenarios 1 and 2) and the internal average temperature is reduced by 1°C (scenario 4). The change in CO_2 emissions due to the switch to electricity (scenario 3) as the primary fuel source is not included (because the effect will depend on the mode of the additional electricity generation), although the health implications are.

See **Online** for webappendix

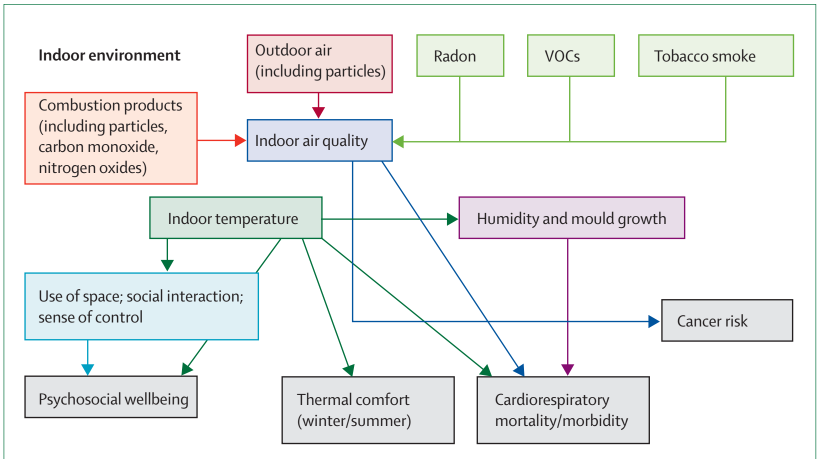

Figure 2: **Connections between the built indoor environment and health**
VOCs=volatile organic compounds.

Panel 2: Core assumptions of UK model

Baseline

- 2010, with population and health status based on WHO projections (Comparative Risk Assessment exercise); building stock, external air pollution, and weather conditions as they are at present.

Mitigation scenarios*

- No projection: instantaneous implementation assumed, as though present conditions are fully replaced with 2010 scenario conditions.
- Based on existing technology (no assumption of new or improved technology).

Health estimates

- Derived from attributable burdens calculated with adaptation of Comparative Risk Assessment method—assumes changes in health for each scenario are represented by the difference in modelled exposures compared with baseline, from which attributable burdens are computed with relevant relative risks and 2010 mortality and disease rates. Changes in burdens of chronic disease and lung cancer are counted, irrespective of probable time lags.
- Years of life lost computed as difference between age at death and the theoretical optimum life expectancy at that age, which, to be normative across populations, is always calculated with reference to life tables representing the best in the world.[45]
- No time discounting or age-weighting applied in disease burdens.
- No inclusion of indirect health effects (eg, those operating through economic pathways) or of those arising from success in restricting climate change.

*Panel 1 shows descriptions of specific scenarios.

increasingly expensive for national budgets. This situation adds to the attraction of deployment of advanced biomass stoves that provide high performance, use local renewable resources, and relieve the government of the cost of fuel subsidies. Climate change is a major threat and household fuel combustion is an important contributor, especially to black carbon, with high greenhouse effects per unit energy delivered compared with many other human uses of energy, depending on the relative weighting of the climate-active pollutants emitted (webappendix p 10).

In view of the combined goals of energy security, health protection, and minimisation of changes in climate, the best approach is to move toward advanced combustion devices with high combustion efficiency and low emissions, such as so-called gasifier stoves. Even well operated chimney stoves do not provide these benefits. To achieve reliable high performance, stoves should use either ceramics or customised metal alloys, neither of which can be effectively manufactured at village level, but have to be made in central manufacturing facilities with good quality control and other modern mass-production techniques. Truly improved stoves tend to have a narrow tolerance to fuel size and moisture and thus generally need increased fuel processing in households or, for high performance, preprocessing as pellets or briquettes. Hybrid gasifier stoves (with small electric blowers), however, effectively maintain good performance for a wide range of fuel characteristics. Microchip and personal computer developments offer cost-effective ways to monitor and assess programmes covering millions of households.

Close to two-thirds of rural Indian households now have access to electricity for at least part of the day—which is a substantial change since the 1980s. This development makes use of advanced blower stoves that are feasible in much of the country. The Rajiv Gandhi Scheme[15] to electrify all households should bring this benefit to an even greater proportion in coming years. Widespread access to radio, television, and cell phones and growing access to the internet provide new ways to market, monitor, and otherwise facilitate stove sales and dissemination. Improvements in health infrastructure in rural India could be used for dissemination of stoves, including the growth of the Anganwadi Centres Programme,[16] a network of prenatal care clinics, which by the middle of the decade was already helping to provide 77% of all pregnant women with check-ups, education, and drugs.[17]

Advanced biomass stoves sold in India today achieve some 15 times fewer particle emissions per meal than do traditional stoves,[18] thereby promising substantial reductions in air pollution exposure and health-related burdens. Prices are $20–50, and more than half a million have been sold so far. Although no major studies have been done directly investigating the effect of such stoves on health, since they produce little smoke they arguably achieve better exposure reduction than do chimney stoves that merely divert the smoke a short distance, and could rival benefits seen with clean fuels.[19,20]

	Health effects	Relative risk used	Principal sources of evidence and comments
Particle pollutants*†	Cardiopulmonary mortality; lung cancer	1·059 per 10 μg/m³; 1·082 per 10 μg/m³	US cohort, outdoor air[46,47]
Radon	Lung cancer	1·16 per 100 Bq/m³ increase in usual radon concentrations	Collaborative analysis of data from European case control studies of radon in homes[29]
Carbon monoxide exceedance	Death from acute carbon monoxide toxicity	Rate of one death per million people assumed for dwellings with combustion appliances	Health Protection Agency data for acute carbon monoxide poisoning[48]
Second-hand tobacco smoke	Myocardial infarction; cerebrovascular accident	1·30 if in same dwelling as smoker; 1·25 if in same dwelling as smoker	Meta-analyses[49,50,51]
Mould growth	Respiratory symptoms	1·50	US Institute of Medicine report and meta-analysis on dampness/mould[32,33]
Cold‡	Cardiovascular mortality	−2·0% reduction in excess winter death per °C increase in standardised winter indoor temperature	Epidemiological analyses of cold-related mortality risk in relation to indoor cold in England[52]

*Particulate matter with aerodynamic diameter 2·5 μm or less. †Effects of exposure to nitrogen dioxide (respiratory symptoms at high concentrations) and volatile organic compounds (possible allergic or respiratory symptoms especially in children) were not quantified because the evidence was considered too uncertain.[53] ‡Standardised indoor winter temperature at 5°C outdoor temperature.

Table 2: **Exposures and health effects included in models**

Our analysis does not assume health benefits greater than those suggested by meta-analyses of previous studies reported as part of the WHO Comparative Risk Assessment comparing traditional use against a mixture of less advanced improvements and clean fuels.[21] Since the high reductions that advanced stoves are capable of producing could well be lessened in the field, where fuel and operator variability are high, extrapolation beyond present evidence is unwise.

The decade-long 150-million stove programme is certainly ambitious, but actually at the same rate and less in total than the 180 million stoves achieved in the Chinese national programme in 12 years[14] starting in 1983 with a national population then similar to that of India today. Additionally, India would have 25 years more experience to work from. The new programme should implement a range of different dissemination modes, including those aimed at the most vulnerable populations. An attractive mode would be to include dissemination as part of pre-natal examinations within the prenatal clinic system. In addition to targeting of the most vulnerable group, pregnant women and their unborn children, these women are already being identified and contacted. If targeted only at first pregnancies, this strategy would cover 7–8 million households a year, about half the requirement. The remainder could be introduced through targeted subsidies to other population groups, perhaps linked to the electrification programme, since in general these advanced stoves are too expensive for poor households to pay the full cost, even though they receive the direct benefits of fuel savings. Similar to what has happened in other countries, the international carbon market, either through the official Clean Development Mechanism[22] or the voluntary Gold Standard system,[23] can help to offset part of the cost.

Modelling changes in health

We began by mapping the complex connections between energy production and use as it relates to the built environment (webappendix p 2).[24] We concentrated on the part of this scheme that relates to the indoor

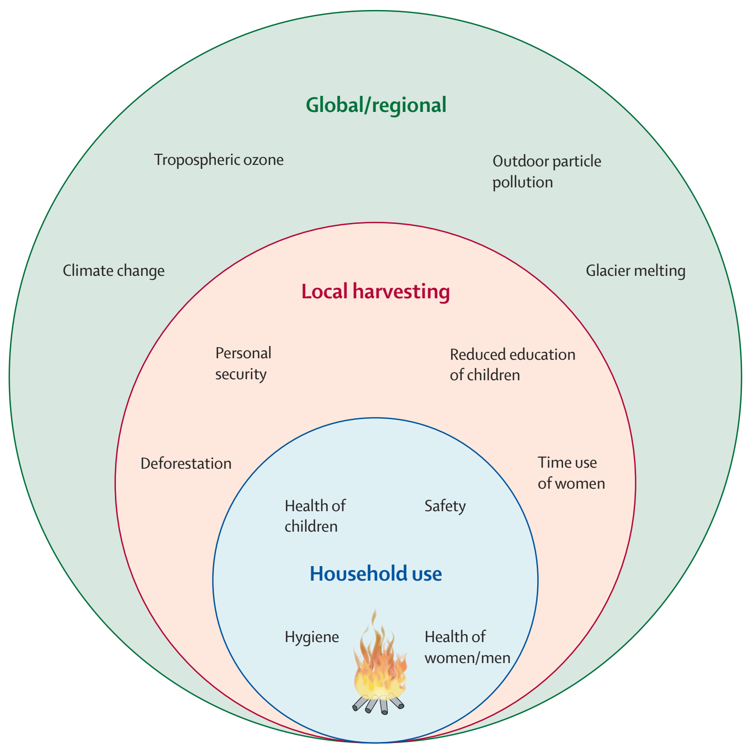

Figure 3: **Effects of traditional household fuel use**
This figure illustrates the wider effects of traditional household biomass fuel use. Here, however, we quantify only the direct effects on health and global climate.

environment (figure 2). The changes in health relating to energy supply systems for commercial energy are partly addressed in a separate report about electricity generation[25] and are not considered here. Nor did we include the role of household fuel combustion on outdoor air pollution, or the health benefits operating through climate-change mitigation, despite their evident importance.[26,27] Because of uncertainties we also did not directly address pathways relating to fuel cost, household

	Fabric improvements	Improved ventilation control	Fuel switching	Occupant behaviour	Combined
Premature deaths					
$PM_{2·5}$	0	–32	–64	0	–107
Radon	0	3	0	0	3
CO	0	0	–1	0	–1
ETS	0	24	0	0	24
Mould	0	0	0	0	0
Cold	–7	–1	0	0	–8
DALYs					
$PM_{2·5}$	0	–310	–619	0	–1026
Radon	0	43	0	0	43
CO	0	0	–25	0	–25
ETS	0	219	0	0	219
Mould	–2	12	0	5	15
Cold	–60	–12	0	0	–72
Totals					
Premature deaths	–7	–6	–65	0	–89
DALYs	–62	–48	–644	5	–847
Change in disease burdens per megatonne CO_2 saved					
Premature deaths	–12·2	–64	..	0·0	–133
DALYs	–115	–492	..	17·3	–1267

Data are change per million population compared with baseline (2010). Negative values show reductions in disease burdens. $PM_{2·5}$=particulate matter with aerodynamic diameter 2·5 μm or less. CO=carbon monoxide. ETS=environmental tobacco smoke. DALYs=disability-adjusted life-years. CO_2=carbon dioxide.

Table 3: **Health effects of the UK built stock scenarios**

budgets, and energy security, although these again might have important health implications in both developed and developing countries. We therefore defined a small range of pathways for quantitative modelling, the most important of which relates to combustion sources and ventilation characteristics, which have bearing on the concentration of pollutants[28] such as radon,[29,30] second-hand tobacco smoke,[31] and dampness and mould,[32–38] especially in low-income households.[24,39–44]

Quantitative modelling of changes in health burden for the case studies is described in the webappendix pp 3–10. The basis of the calculations differed between the two settings. For UK household energy scenarios, estimated changes in health were calculated from the difference between 2010 (present) exposures and those that would occur under mitigation, assuming that circumstances are otherwise held constant at 2010 conditions. Panel 2 summarises our core assumptions and table 2 details exposures and health effects included in the models. We assume an instantaneous implementation of the proposed mitigation measures, with no other change. This approach avoids the need for uncertain projections, and the effect of mitigation measures is clear because these are the only changes. We chose this approach in part because a substantial degree of improvements in household energy efficiency will probably be implemented with time anyway, so specification of a future counter-factual baseline is difficult. The disadvantage, however, is that this approach does not take account of potentially important trends in exposure that are unrelated to climate change mitigation policies, and it does not show a timecourse of implementation.

For the India case study, we were able to specify a 10-year staged implementation plan and adapt methods accordingly. Many health-related effects have been associated with inefficient household use of simple biomass fuel, not only within the household but also in the local community and worldwide (figure 3). In this analysis, however, we quantify the effects of improvements in terms of indoor air pollution alone (mainly health of women and children). As in the UK study, the baseline was 2010, but cumulative health effects of the 10-year staged implementation were calculated on the basis of WHO projections of baseline health status for 2020, in addition to projections for population and the slow natural transition to clean fuels, to improve estimates of underlying mortality and morbidity rates for intervening years. For more direct comparison with UK results, we also computed the beneficial effect of the cookstove programme using the same methods as for the UK study (as if fully implemented under 2010 conditions).

Outcomes

UK household energy efficiency programme

All UK energy efficiency scenarios, with important caveats, result in an overall benefit to health, but with some negative effects relating to specific forms of exposure (table 3). For the fabric improvement scenario (scenario 1) we assumed that fabric improvements did not change ventilation characteristics and that the effect on health was confined to temperature effects arising from reduced heat loss. The changes in health consisted of both direct effects on winter mortality and potentially morbidity[52,54–59] and indirect effects via changes in mould growth.[60] The modelled improvements were limited to technically plausible increases in insulation, entailing a shift in the dwelling stock distribution of thermal efficiencies.

Ventilation-system improvements (scenario 2), through changes in air exchange, had effects on indoor air quality and temperature. The most notable change was reduction of particle concentrations. Our specification for this scenario was to install mechanical ventilation systems in the most airtight 21% of dwellings (ie, those with permeability reduced to 3 m^3/m^2 per h), since this system provides potentially the most effective control of ventilation and recovery of heat (webappendix p 27). All other dwellings were assumed not to have mechanical ventilation systems, but to have improvements in air tightness only. Dwellings with mechanical ventilation benefit from high air exchange rates, and so exposures for pollutants from internal sources (tobacco smoke, etc)

	Baseline (2010)	Change compared with baseline				
		Fabric improvements (scenario 1)	Improved ventilation control (scenario 2)	Fuel switching (scenario 3)*	Occupant behaviour (scenario 4)	Combined (scenario 5)
Pollutant concentrations†						
$PM_{2.5}$ (μg/m³)‡	5·5	0·0	–0·9	–1·8	0·0	–3·0
NO_2 (% of hourly averages exceeding 400 ppb)§	0%	0%	0%	0%	0%	0%
CO (probability of poisoning)	10^{-6}	0	0	-10^{-6}	0	-10^{-6}
Radon (Bq/m³)¶	21·7	0·0	4·5	0·0	0·0	4·5
ETS (ratio of exposure compared with baseline)¶	1·0	0·0	0·1	0·0	0·0	0·1
Dampness or humidity-related						
Mould growth (% with mould index >1)	17·7%	–0·4%	2·6%	0·0%	1·0%	3·1%
Temperature						
Winter indoor temperature (cold) (°C)‖	18·1	0·3	0·1	0·0	–0·2	–0·4
Greenhouse-gas emissions**						
Reduction in CO_2 emissions versus 2010 baseline (megatonnes)††	··	33	6	0	2	41
Reduction in CO_2 versus 1990 (megatonnes)‡‡	14	47	20	14	16	55

$PM_{2.5}$=particulate matter with aerodynamic diameter 2·5 μm or less. NO_2=nitrogen dioxide. ppb=parts per billion. CO=carbon monoxide. ETS=environmental tobacco smoke. CO_2=carbon dioxide. *Scenario assumes removal of all cooking-related $PM_{2.5}$ (via removal of combustion sources and addition of high capture efficiency cookstove hoods). †Values are for indoor air, but for calculation of attributable disease burdens, we assume change in exposure applies to 85% of the time-activity of all individuals; exposure for the remaining time (ie, spent outdoors and in other buildings) is assumed to remain unchanged. ‡Weighted average values of kitchen (10%), lounge (45%), and bedroom (45%). §Data for kitchen only. ¶Data for living room only. ‖For winter indoor temperature, scenario 5 combines scenarios 1 and 2, excluding 4. **Emissions relate to CO_2 only; CO_2 equivalents are around 5% higher, but have not been separately quantified for these scenarios; energy needed to implement the retro-fit is not taken into account—only the change in operating energy use; we assume a stock average heating system efficiency of 0·75. ††We assume no change to CO_2 emissions from fuel switching because the contribution could be negative or positive dependent on form of electricity generation. ‡‡CO_2 saved between 1990 and 2010 is added to the figures for 2010 baseline to show total saving compared with 1990 level.

Table 4: **Changes in exposure† and carbon dioxide emissions in the UK built stock scenarios**

were reduced. However, dependent on external conditions, the high rate of air exchange might draw increased particle pollution into the dwelling from outside. Fortunately, air filters are readily available for mechanical ventilation systems, and in our models, for illustrative purposes, we assumed 80% effective reduction of particle influx.

In dwellings without mechanical ventilation but with increased air tightness, particle concentrations also fell because of reduced ingress from outdoor air. The assumed national average background external concentration of particulate matter with aerodynamic diameter 2·5 μm or less ($PM_{2.5}$) is 13 μg/m³ (informed by DEFRA).[61] The average baseline indoor concentration might thus seem low compared with measured data reported elsewhere (eg, Lai and colleagues[62]). The indoor/outdoor ratio is also crucially dependent on assumptions related to kitchen window opening, internal door opening, and extract fan use, for example. Additionally, the emission rate for $PM_{2.5}$ does not include any contribution from indoor activities such as smoking and (because of an absence of suitable data) cleaning and general resuspension.

The balance of ventilation change in this scenario is such that other pollutants from indoor sources (or under-house sources in the case of radon; webappendix p 27) increased. Thus, the radon-associated burden of deaths caused by lung cancer increased by around three premature deaths per million of the UK population, and those from environmental tobacco smoke by around

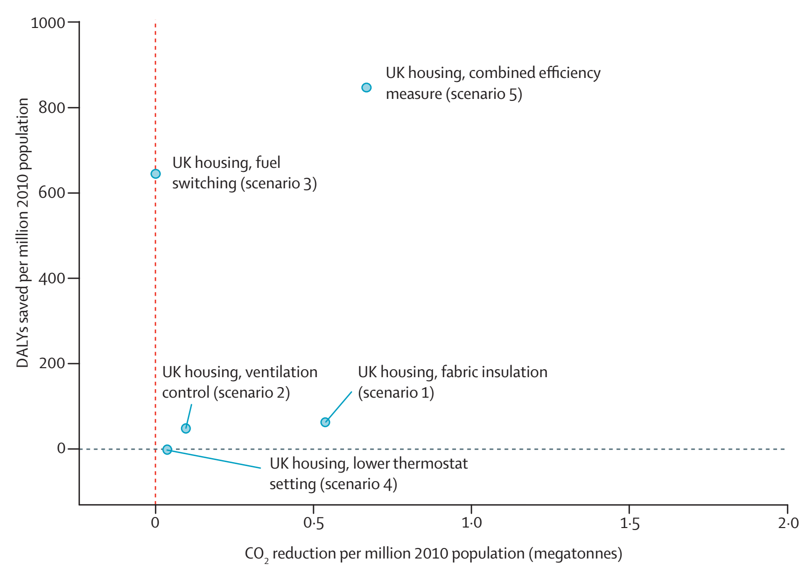

Figure 4: **Estimated effect of the UK household energy scenarios on disability-adjusted life-years saved and reduction of carbon dioxide emissions**
Calculations included the entire UK population in 2010. DALYs=disability-adjusted life-years. CO_2=carbon dioxide.

24 deaths per million (table 3). Although radon concentrations higher than the UK action concentration of 200 Bq/m³ can be dealt with by remediation measures, this process would need a very large number of dwellings to be monitored for increases in radon since our scenarios imply upgrades to the entire housing stock. Moreover,

	Indian population (millions)	Average number of people per household	Baseline				Stove intervention programme			
			Number of households (millions)	Number of households with traditional stoves (millions)	Fraction of traditional stoves	Population using traditional stoves (millions)	Improved stoves distributed (millions)	Number of households with traditional stoves (millions)	Fraction of traditional stoves	Population using traditional stoves (millions)
2010	1214*	4·8	252	187·1	0·74	898·1	15	172·1	0·68	826·1
2011	1228	4·8	258	187·5	0·73	890·9	15	157·5	0·61	748·3
2012	1242	4·7	264	187·8	0·71	883·6	15	142·8	0·54	671·9
2013	1256	4·7	270	188·1	0·70	876·3	15	128·1	0·48	596·8
2014	1270	4·6	276	188·4	0·68	868·9	15	113·4	0·41	523·1
2015	1285	4·6	281	188·7	0·67	861·5	15	98·7	0·35	450·7
2016	1299	4·5	287	189·0	0·66	854·0	15	84·0	0·29	379·5
2017	1313	4·5	293	189·2	0·64	846·6	15	69·2	0·24	309·7
2018	1327	4·4	300	189·4	0·63	839·0	15	54·4	0·18	241·1
2019	1341	4·4	306	189·6	0·62	831·5	15	39·6	0·13	173·7

Percentage of households naturally converting to clean fuels (without stoves) because of economic growth are from reference 9. *Population data from WHO and National Family Health Survey (reference 17).

Table 5: **Population, number of households, and proportion of households with and without improved stoves at every year of the India cookstove intervention**

much of the adverse effect would still occur because of the large number of dwellings with increases in radon to values less than 200 Bq/m³.

Overall, in our particular scenarios, these detrimental changes were more than offset by the reduction in particle exposures, but the balance of risks and benefits varies between dwellings. One area of particular uncertainty and concern, however, is what could occur if mechanical ventilation systems were not properly installed, operated, or maintained or if they broke down. In these circumstances, affected dwellings might have very low air exchange rates, with probable substantial detrimental effects on indoor air quality. In the UK there is as yet insufficient large-scale experience with such systems in households to know how they are likely to operate in real life in the long term.

We assumed that switching to electricity (scenario 3) removes all indoor sources of combustion-related pollutants and cooking-related $PM_{2·5}$. We assumed no change in ventilation characteristics, although in reality a change could occur in some dwellings because of removal of open flues and chimneys, and we assumed that the opportunity was taken to fit high capture efficiency hoods to cookstoves. The reduced health burden came from lowered exposure to fine particles, and the small but important reduction in risk of poisoning from carbon monoxide. With no indoor combustion, there is no indoor source of carbon monoxide (tables 3 and 4). Because we did not model health effects operating through unaffordable fuel costs that cause poverty, we showed no other adverse effects. However, under present conditions, electricity generated from renewable sources is appreciably more expensive than is generation of coal or gas in the UK, although this difference will diminish as fossil-fuel costs increase. This cost is likely to have a disproportionate burden on low-income families, increasing levels of fuel poverty,[4] unless fuel switching is combined with other measures to reduce energy needs or with financial protection for poor households.

The results of the occupant behaviour scenario (scenario 4) were the most difficult to interpret, not only because of the scarce and uncertain evidence about temperature thresholds for cold effects, but also because of the uncertainty about whether and how people are likely to comply. We made the simple assumption of a resetting of thermostat temperatures in winter to result in average temperatures 1°C lower than present values in dwellings with temperatures above 18°C. We therefore made the uncertain assumption that, because the change occurred only in the warmest homes, there was no adverse effect on temperature-related mortality or morbidity. In reality, this situation would be difficult to specify, and personal choices are complex. Much variation is therefore likely—evidence suggests that indoor temperatures in UK dwellings have risen substantially since 1970, along with energy use per person, whereas energy use per unit of disposable income has fallen.[12]

The combined scenario (scenario 5) would achieve the largest benefit to health. Reductions in dwelling CO_2 emissions associated with the scenarios are substantial (table 4). Emissions in the combined scenario compared with the 2010 baseline are reduced by 0·6 megatonnes of CO_2 per million population per year. If reductions in this scenario are added to the reduction already achieved since 1990,[7] CO_2 emissions from dwellings are reduced by 36% compared with the 1990 baseline. This decrease is still short of the 50% target, but we made no allowance for a change to a lower carbon intensive energy supply, and made no specification of changes in device efficiency, including electrical equipment, and space-heating and water-heating devices.

The greatest gain in health from the individual scenarios (ie, excluding the combined scenario) was fuel switching, mainly because of reductions in particle exposure (figure 4). However, in terms of avoided disability-adjusted life-years (DALYs) per tonne of CO_2 saved the greatest gains occur in the ventilation improvement scenario (table 3). The results suggest that there are appreciable benefits of measures to improve the energy efficiency of dwellings through improvement to the fabric and ventilation, but some of the apparent benefit relates to ventilation system changes and air filtering of mechanical ventilation systems. These benefits could be substantially reduced if systems are not well fitted, operated, and maintained. Details of sensitivity analyses of changes in exposure under different assumptions of ventilation and external $PM_{2·5}$ concentrations are provided in the webappendix p 26.

Cookstove programme for India

Table 5 shows the numbers of improved cookstoves implemented in every year of the India cookstove programme, and figure 5 the premature mortality that could be prevented—ie, the avoidable burden for every outcome. At the end of the period, 87% of Indian households would have clean combustion, either through graduating on their own to clean fuels or receiving advanced biomass stoves as part of the intervention. By 2020, the total number of averted premature deaths from acute lower respiratory infections will have reached about 240 000 children aged younger than 5 years, and more than 1·8 million premature adult deaths from ischaemic heart disease and chronic obstructive pulmonary disease (COPD) will have been averted (table 6).

Figure 6 shows the total number of DALYs averted from the three diseases and the contribution of each to the total. Overall, the national burden of disease (DALYs) in 2020 from these three major diseases would be about a sixth lower than it would have been without the stove programme—which is equivalent to elimination of nearly half the entire cancer burden in India in 2020.[63] About half the total health benefit is in the form of averted COPD, with ischaemic heart disease and acute lower respiratory infections sharing the other half more-or-less equally. In reality, the health benefit for acute lower respiratory infections in children accrues almost immediately on introduction of stoves. The benefit for ischaemic heart disease, however, occurs more slowly, and for COPD slower still. Thus, by 2020, the benefits for these diseases have not yet been fully realised and the figures should be interpreted as the committed avoided ill health—ie, the total avoided ill health that would eventually be realised from operation of the improved stoves between 2010 and 2020.

The climate benefits of such a major shift in household combustion are also substantial. There would be

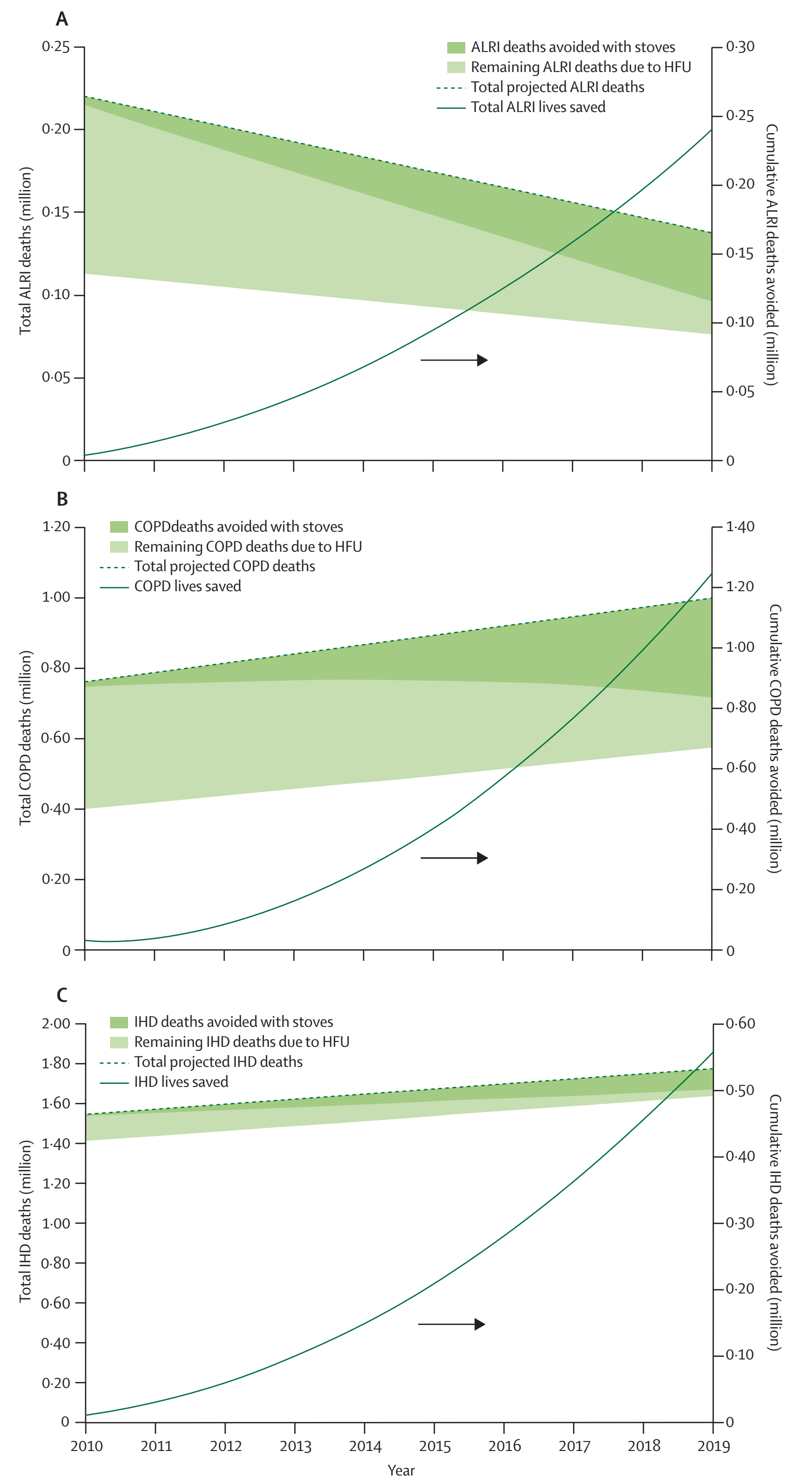

Figure 5: **Premature deaths avoided by large-scale introduction of low-emissions stoves in India**
(A) Deaths from acute lower respiratory infections (ALRI) in children aged younger than 5 years; (B) chronic obstructive pulmonary disease (COPD) in adults aged older than 30 years; and (C) ischaemic heart disease (IHD) in adults aged older than 30 years. HFU=household fuel use. Dotted lines show estimated mortality trends without intervention (from WHO estimates). Solid areas beneath dotted lines show mortality avoided by the stove programme, and dotted areas show total mortality from traditional solid fuel use without improved stoves. Right axes plot cumulative total premature deaths avoided by improved stoves.

	Deaths from ALRI	Deaths from COPD	Deaths from IHD	Total DALYs for these diseases
Avoided in 2020 (%)	30·2%	28·2%	5·8%	17·4%
Annual number in 2020 without stoves (×10⁶)	0·14	1·00	1·77	63·0
Total avoided 2010–20 (×10⁶)	0·24	1·27	0·56	55·5

ALRI=acute lower respiratory infections. COPD=chronic obstructive pulmonary disease. IHD=ischaemic heart disease. DALY=disability-adjusted life-year.

***Table 6:* Health benefits of the Indian stove programme**

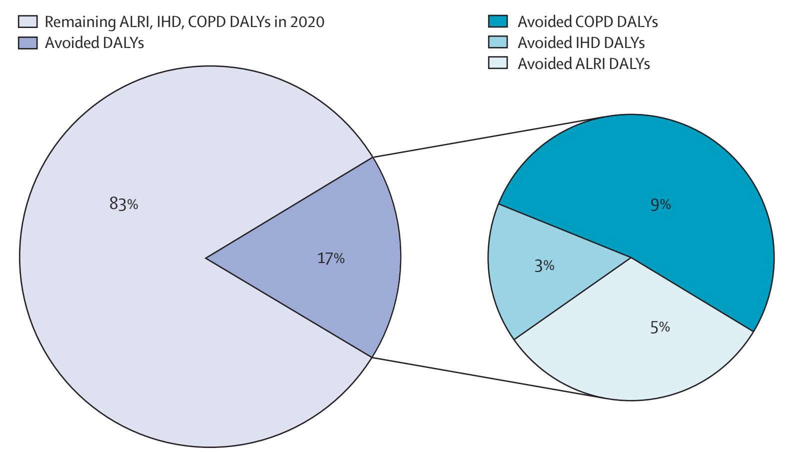

***Figure 6:* Health benefits of Indian stove programme after completion in 2020**
Estimated disability-adjusted life-years (DALYs) from acute lower respiratory infection (ARLI), chronic obstructive pulmonary disease (COPD), and ischaemic heart disease (IHD) that could be avoided in India in 2020, compared with total DALYs for these diseases.

decadal reduction of about 14 megatonnes of methane and 0·5 megatonnes of black carbon, each representing substantial reduction in direct global warming. Additionally, there would be a reduction of nearly 100 megatonnes carbon monoxide and 40 megatonnes non-methane volatile organic compound emissions, which would otherwise contribute to ozone formation. Ozone is not only a greenhouse gas but is also damaging to health and ecosystems. Dependent on metrics applied, these emissions reductions (of methane, black carbon, carbon monoxide, and non-methane volatile organic compounds) could be equivalent to 0·5–1·0 billion tonnes CO_2 equivalent during the decade (webappendix p 10). Finally, the reduction in overall particle emissions, although partly countering the global climate benefits of reduction of black carbon (because of the cooling effects of some types of particles), would have substantial benefits for lessening of regional outdoor air pollution, climate disruption, and the solar dimming that adversely affects agriculture in south Asia.[64]

The benefit of the cookstove programme, if assessed on the same basis as for UK housing scenarios (2010 population with and without mitigation), would give rise to a saving of around 12 500 DALYs and 0·1–0·2 megatonnes CO_2 equivalent per million population in 1 year, compared with 847 DALYs and 0·6 megatonnes CO_2 per million population in 1 year for the UK combined scenario.

Discussion

The modelling we have presented should be interpreted as illustrative of the scale of health benefits that are associated with selected strategies aimed at abatement of emissions of greenhouse pollutants. The broad conclusion is clear—that in both high-income and low-income settings there is a set of abatement actions with appreciable potential overall benefits to health. In the contrasting examples we investigated, the health benefits seem especially great for the populations of India that rely on inefficient combustion of biomass fuels for household energy. Evidence from many studies shows that women, children, and men in such settings are exposed to very high concentrations of particles, gases, and other noxious pollutants that are often at least an order of magnitude higher than the health-protection values set by national and international agencies. Further, these populations might be especially vulnerable to the health consequences of breathing such pollution because of poor nutrition, poor access to health care, and other risk factors.

We should note that the models we developed are somewhat artificial constructs that, necessarily, do not provide accurate real-life representations of population health or, in the UK example at least, the timecourse during which the proposed changes might take place. The programmes that have been implemented in the UK, such as Warm Front, although probably beneficial for health,[65] are much more restricted in the type of energy efficiency upgrading than is implied by our scenarios, and are much more restricted in coverage of the built stock. Our scenarios are therefore very ambitious, but technically feasible, and are necessary to achieve the abatement goals set out by the UK Climate Change Committee. They will also need much political will and public motivation to bring about.

Our models assume that exposure-related changes in health took place without lag, and that attributable burdens equate to preventable burdens—which are both oversimplified assumptions. In reality, the world is not static but is full of rapid change in its population, health status, pollution levels, technology, and socioeconomic development, and although these and other trends can in theory be accounted for, there is substantial complexity in attempting to do so.

We were also restricted to modelling only a subset of possible pathways to health. Notable omissions are those relating to economic effects both at a macroeconomic level and in terms of household budgets, as well as those of climate change itself. For example, improvements in efficiency and cleanliness of household fuel in poor countries are highly cost-beneficial, a major contribution of which is the time saved for women.[66,67]

The interpretation of findings assumes causality and reversibility of exposure–response links and accuracy in estimation or modelling of changes in exposures, all of which entail uncertainties. Furthermore, several of our simplifying assumptions probably lead to overestimation of the health benefits of abatement interventions; for example, by failing to account for falling outdoor particle pollution or trends of improving health status and by assuming immediate and complete reversal of exposures—even leaving aside how long implementation of the abatement changes we specified would take in reality. Conversely, for the India example, we have used a conservative assumption for particulate reductions with ischaemic heart disease and did not include several health outcomes with potentially large population effects (eg, low birthweight) for which evidence was not sufficiently robust at the time of the 2004 Comparative Risk Assessment, but additional evidence has accrued since.

The limitations of our models are important, but should not deflect from the main message. Overall, they provide important comparative evidence of the possible type and scale of local environmental health effects that can be expected from pursuit of mitigation policies. The evidence adds to the case for acceleration of mitigation because of the probable health benefits, and shows the differences in interventions in high-income and low-income settings. Housing interventions in the UK have a greater effect on reduction of CO_2 per dwelling than they do in the India case study, and are essential for that reason alone. However, the potential health benefits, although generally positive and significant, are small by comparison with those of improved cookstove technology in India, showing the large burden that is associated with inefficient burning of solid fuels. Our results are consistent with the findings of the most authoritative health risk assessment of this hazard, which suggested that in 2000, around 950 000 children worldwide died each year from acute lower respiratory infections, along with about 650 000 premature deaths of women from COPD and lung cancer (in coal-using populations).[9,68] At 2·7% of the total global burden of disease, these factors place household air pollution second after poor water and sanitation among environmental causes of ill health. In poor countries, household air pollution ranks even higher, and causes in India, for example, about 4% of all lost healthy life-years.

Replacement of inefficient cookstove technology will be a very important public health measure. Although improved stove programmes in the past have not always been successful, some have achieved remarkable penetration. The historical model used here, the Chinese national improved stove programme during the 1980s and 1990s, was able to provide stoves to 180 million rural households.[14,69,70] Typical of such programmes in the past century, however, the technology was able to lower indoor pollution somewhat through chimneys, but did not substantially reduce overall air pollution and greenhouse-gas emissions. Nowadays, however, new stove technologies have the potential to bring emission of products of incomplete combustion from biomass stoves down nearly to those of clean fuels, such as liquefied petroleum gas.

Worldwide, household-fuel combustion causes about a third of the warming due to black carbon and carbon monoxide emissions from human sources, about a sixth of ozone-forming chemicals, and a few percent of methane and CO_2 emissions.[21] When deposited in regions with vulnerable mountain glaciers, black carbon particles contribute to glacier melting.[71,72] This contribution is most crucial in the Himalayan region, where glaciers stabilise summer flow in rivers that supply water and irrigation to 1·5 billion people.

In high-income settings such as the UK, greenhouse-pollutant abatement strategies will necessarily entail major changes in the efficiency of energy use by households and in the dominant forms of energy supply. These changes will have appreciable implications for public health, and are potentially positive through changes to the indoor environment (winter temperatures, air quality) and outdoor air quality. The contrasting example of the cookstove intervention shows the very great potential for improvement of public health by interventions that also have appreciable bearing on climate change mitigation.

Early this decade, the UN Millennium Project called on countries to adopt the voluntary cooking energy target "by 2015, to reduce the number of people without effective access to modern cooking fuels by 50%, and make improved cookstoves widely available". Achievement of this target was regarded as an essential contribution to Millennium Development Goals 4 and 5, which focus on reduction of child and maternal mortality. Although progress is being made, present efforts are very unlikely to lead to achievement of these goals by the target date of 2015.[73] We suggest that the case for far bolder and emphatic action is strengthened by our evidence. Finding of ways to combine or leverage climate mitigation investments to help to accelerate achievement of Millennium Development Goals should have a high priority. Improvements in the household fuel sector offer important potential benefits for health of women and young children as well as for mitigation of climate change.

For the **UN Millennium Project** see http://www.unmillennium project.org

Contributors

All authors participated in the development of ideas for the report. The text was drafted mainly by PW, KRS, and MD, with contributions from all other authors. Data analysis was done principally by ZC, IH, IR, HA, BA, and PW.

Conflicts of interest

We declare that we have no conflicts of interest.

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