BMJ

RESEARCH

Home energy efficiency and radon related risk of lung cancer: modelling study

James Milner *lecturer*[1], Clive Shrubsole *research associate*[2], Payel Das *research associate*[2], Benjamin Jones *lecturer*[2 3], Ian Ridley *senior research fellow*[2 4], Zaid Chalabi *senior lecturer*[1], Ian Hamilton *lecturer*[5], Ben Armstrong *professor in epidemiological statistics*[1], Michael Davies *professor of building physics and the environment*[2], Paul Wilkinson *professor in environmental epidemiology*[1]

[1]Department of Social and Environmental Health Research, London School of Hygiene and Tropical Medicine, 15-17 Tavistock Place, London WC1H 9SH, UK; [2]Bartlett School of Graduate Studies, University College London, UK; [3]Department of Architecture and Built Environment, University of Nottingham, UK; [4]Royal Melbourne Institute of Technology, Melbourne, Victoria, Australia; [5]UCL Energy Institute, University College London, UK

Abstract

Objective To investigate the effect of reducing home ventilation as part of household energy efficiency measures on deaths from radon related lung cancer.

Design Modelling study.

Setting England.

Intervention Home energy efficiency interventions, motivated in part by targets for reducing greenhouse gases, which entail reduction in uncontrolled ventilation in keeping with good practice guidance.

Main outcome measures Modelled current and future distributions of indoor radon levels for the English housing stock and associated changes in life years due to lung cancer mortality, estimated using life tables.

Results Increasing the air tightness of dwellings (without compensatory purpose-provided ventilation) increased mean indoor radon concentrations by an estimated 56.6%, from 21.2 becquerels per cubic metre (Bq/m^3) to 33.2 Bq/m^3. After the lag in lung cancer onset, this would result in an additional annual burden of 4700 life years lost and (at peak) 278 deaths. The increases in radon levels for the millions of homes that would contribute most of the additional burden are below the threshold at which radon remediation measures are cost effective. Fitting extraction fans and trickle ventilators to restore ventilation will help offset the additional burden but only if the ventilation related energy efficiency gains are lost. Mechanical ventilation systems with heat recovery may lower radon levels and the risk of cancer while maintaining the advantage of energy efficiency for the most airtight dwellings but there is potential for a major adverse impact on health if such systems fail.

Conclusion Unless specific remediation is used, reducing the ventilation of dwellings will improve energy efficiency only at the expense of population wide adverse impact on indoor exposure to radon and risk of lung cancer. The implications of this and other consequences of changes to ventilation need to be carefully evaluated to ensure that the desirable health and environmental benefits of home energy efficiency are not compromised by avoidable negative impacts on indoor air quality.

Introduction

Through the 2008 Climate Change Act,[1] the UK government has enshrined in law targets for reducing emissions of greenhouse gases as its commitment towards global action on climate change: compared with 1990 a 34% reduction by 2020, 80% by 2050, and a recommended interim goal of 60% reduction by 2030.[2] A key target for such reduction is the housing sector,[3] for which substantial population wide changes are needed over the coming decades to improve energy efficiency, primarily through better insulation of the fabric (walls, roof, and floor) of dwellings and tighter control of ventilation.

While control of ventilation is good for energy efficiency, indoor temperatures in winter,[4] and protection against outdoor pollutants (notably airborne particles),[5] it has the potential to increase concentrations of pollutants arising from sources inside or underneath the home.[6 7] Notable among these is radon, a naturally occurring inert gas formed from the radioactive decay of elements of the uranium series, which seeps into homes through the floor, especially in areas with predisposing geology and soil type.[8] Radon is the second most important risk factor for lung cancer after smoking and may be responsible for 15 000 to 22 000 deaths from lung cancer each year in the United States,[9] 9% of deaths from lung cancer in European countries,

Correspondence to: P Wilkinson paul.wilkinson@lshtm.ac.uk

Extra material supplied by the author (see http://www.bmj.com/content/348/bmj.f7493?tab=related#webextra)

Supplementary information

and around 1400 cases annually in the United Kingdom.[10 11] Radon is unique in the context of indoor air quality since it is a continuous source, which is therefore not responsive to the intermittent ventilation techniques that can be used to deal with other pollutants at the emission source (for instance, using extraction fans to remove cooking related particulates).

The housing energy efficiency strategy for England will entail an intervention affecting almost all of the 22.3 million dwellings, reducing ventilation rates and increasing radon levels on a population wide basis. This is an issue that has received relatively little attention despite the large scale of planned investments in housing. If these actions are carried out in an inappropriate manner there is potential for a substantial adverse impact on public health that will be embedded in the population for years. We carried out a modelling study to estimate the impact such a strategy may have on radon levels and associated lung cancer mortality.

Methods

The study entailed two main components: building physics modelling of current and future radon levels in the housing stock of England, and a health impact model for lung cancer mortality based on a life table method.

Mitigation scenarios

We modelled indoor radon levels for the present day and for four future scenarios representing a variety of plausible retrofitting strategies, which could be applied to the existing stock to help achieve reduction targets for carbon dioxide emissions. The four future scenarios were:

Scenario 1 (air tightness)—the air tightness of the housing stock is increased in line with (a realistic interpretation of) good practice guidance on reducing uncontrolled ventilation in dwellings to help achieve improvements in household energy efficiency.[12] The specified change for scenario 1 represents a reduction in permeability of dwellings ("air leakiness"), from the current average of 13 $m^3/m^2/h$ at 50 Pa pressure to 7 $m^3/m^2/h$, with a target upper limit for air permeability of 10 $m^3/m^2/h$ (maximum allowed for new builds under Part L of the Building Regulations for England[13] instead of the recommended "good practice maximum" of 5 $m^3/m^2/h$. Moreover, we assumed that 9% of dwellings fail to meet this target and are therefore above 10 $m^3/m^2/h$, a failure rate informed by empirical evidence on currently achieved permeability levels in refurbished[14] and new build dwellings.[15]

Scenario 2 (air tightness+purpose-provided ventilation)—as for scenario 1 but with the addition of partially compensating purpose-provided ventilation (trickle vents and extraction fans) in all dwellings to offset some of the reduction in air exchange. We assumed such purpose-provided ventilation was not used or was non-operational in 40% of dwellings.[16]

Scenario 3 (with mechanical ventilation and heat recovery)—as for scenario 2 but with mechanical ventilation and heat recovery systems installed in the 20% most airtight dwellings (permeability ≤3 $m^3/m^2/h$). Mechanical ventilation and heat recovery systems pump air through dwellings but recover heat from the expelled air, so maintaining relatively high air exchange but with the advantage of heat recovery to save energy. These systems are a potentially efficient solution for very airtight dwellings, the efficiency of which can be identified using a standard blower door test.

Scenario 4 (with mechanical ventilation and heat recovery assumed to include 10% failures)—as for scenario 3 but assuming that 10% of mechanical ventilation and heat recovery systems fail or are not used appropriately.

Modelling radon levels

For each of the present day and future stock scenarios, we modelled the distribution of indoor radon levels using the validated multizone model, CONTAM.[17] We modelled 10 housing archetypes (seven archetypes of houses and three of flats) under a range of ventilation strategies (purge (window opening) ventilation only or purge ventilation plus either trickle ventilators or extraction fans (in bathrooms and kitchens), or both) depending on dwelling type and age. We also modelled the inclusion of mechanical ventilation and heat recovery systems for the most airtight dwellings. Operational characteristics of extraction fans, trickle ventilators, and mechanical ventilation and heat recovery systems were matched to UK industry norms and specified to comply with minimum whole house ventilation rates required by Approved Document F of the Building Regulations for England and Wales.[18] We matched the present day (baseline) frequency of archetype and ventilation method combinations to data from the English Housing Survey 2009.[19] The distribution of air permeabilities in dwellings (see supplementary fig 1) was based on extensive survey measurements.[20] Figure 1⇓ shows the modelled ventilation rate (air changes per hour) distribution for each scenario.

We applied a radon emission rate to all dwellings proportional to the area of the ground floor rooms.[21] We assumed that flats on the first floor had 50% of the ground floor radon levels, whereas flats above the first floor were not affected by radon.[22] To account for geographical variations in radon levels, we constructed models for areas of low, medium, and high radon exposure by multiplying the modelled exposures by factors determined by calibration against observed data.[23]

Greenhouse gas emissions

We estimated the space heating demand of the stock due to ventilation heat losses using the standard degree hour method,[24 25] assuming a heating efficiency of 77%.[26] This was used to estimate the corresponding greenhouse gas emissions for England in megatonnes of carbon dioxide equivalent (Mt CO_2e) based on the current carbon intensity[27] and under decarbonisation assumptions consistent with the UK's 2020 and 2030 climate change mitigation targets.

Modelling impact on lung cancer mortality

We estimated the impact of altered radon levels on lung cancer mortality using life table methods based on the IOMLIFET model,[28] populated using age specific population data and 2009 rates for all cause and lung cancer specific mortality for England and Wales obtained from the UK Office for National Statistics. The model estimates patterns of survival in the population over time, with outputs including changes in the number of deaths and life years lived each year. To perform the health impact assessment, we adjusted the mortality rates in response to the changed exposures to radon and the outputs compared against those of the baseline (unadjusted) life tables. We modelled health impacts over a follow-up period of 106 years; long enough for the original birth cohort to have died out (105 was maximum age in life table). For the main analyses, we assumed no changes in the underlying health status of the population over time, which previous work has shown has only a minor effect on life table calculations.[29]

To make clearer the impact of changes in ventilation, we assumed an instantaneous step change in stock ventilation characteristics under each of the future scenarios. In reality, implementation would be phased over time. However, we did incorporate time dependent functions to model the latency between change in exposure and changes in lung cancer mortality. The assumed sigmoid onset lag for increased exposure assumed close to zero excess risk within 10 years of increased exposure and a gradual rise to almost full excess risk by 20 years. For reduced exposure, the assumed cessation lag was an exponential decline (see supplementary fig 2). In both cases, we applied a proportion of the relative risk each year after the intervention, with the full relative risk applied after 20 years.

We assumed a linear no threshold model for the relation between radon level and risk of lung cancer with a 16% increase in lung cancer mortality risk per 100 Bq/m^3 based on evidence from European case-control studies.[10 30] This relation has been corroborated by other studies and meta-analyses[31 32] and is consistent with evidence that radon is a likely carcinogen at all exposure levels.[33]

As smokers have a greatly increased risk of lung cancer (although their radon related risk is proportionate in relative terms to that of non-smokers),[10 34] we used separate life tables for smokers and non-smokers, assuming lung cancer rates in smokers to be 25 times that of non-smokers.[10] Information on the current smoking prevalence in England (21% in 2009) was based on survey data.[35] In the base case scenario, we assumed a 50% decrease in lung cancer prevalence to account for the lagged effect of the roughly 50% decrease in smoking in the past 30 years on future underlying lung cancer mortality rates, but no further decreases in lung cancer rates owing to possible further future reductions in smoking. However, in sensitivity analyses, we did examine the effect of lower future smoking prevalence (of 15% and 10%) as well as of removing the lagged effect of the recent decline in smoking prevalence. We did not model synergistic effects of environmental (second hand) tobacco smoke on lung cancer risk as presently evidence allowing accurate quantification of such impacts is insufficient.

Results

Radon levels

We calibrated our model based estimates of current radon levels to approximate the observed distribution for England and Wales (modelled mean 21.2 Bq/m^3, mean from survey data 21.0 Bq/m^3) (see supplementary fig 3).[23 36] Table 1⇓ summarises the radon levels under present day and each of the four future scenarios (see also supplementary fig 4). With the increased air tightness of scenario 1, radon levels increase by 56.6% from the present day mean of 21.2 Bq/m^3, to 33.2 Bq/m^3. A substantial increase also occurs in the proportion of dwellings above the Public Health England Action Level of 200 Bq/m^3.[34] The increase from 0.6% to 2.0% would represent a further three quarters of a million people living in homes with radon above the Action Level.

In scenario 2, the addition of purpose-provided ventilation (assumed to operate correctly in 60% of homes) reduces the increased radon levels but does not restore them to present day levels. However, models that (unrealistically) assume 100% operation for purpose-provided ventilation in fact reduce radon to marginally below current levels (data not shown).

Assuming mechanical ventilation and heat recovery is installed in the 20% most airtight dwellings (scenario 3) has a considerable impact, reducing both the number of homes with the highest levels of radon and the population mean to 19.6 Bq/m^3, slightly below current day levels.

Assuming a 10% failure in mechanical ventilation and heat recovery systems (scenario 4) results in only a modest increase in the mean, to 21.8 Bq/m^3, because the failure affects only 2% of the housing stock (10% of the 20% with mechanical ventilation and heat recovery). However, people in homes with failure of mechanical ventilation and heat recovery systems would experience substantial increases in radon levels, of more than 1000 Bq/m^3 in some circumstances, although it is likely that many homeowners would eventually fix such faulty systems or adjust their behaviour (for example, by opening windows more often) to improve air exchange.

Health impacts and greenhouse gas emissions

Translation of our modelled distribution of present day radon levels into risk of lung cancer mortality suggests that current levels account for around 1000 deaths per year in England, a figure slightly lower than published estimates.[11 23] More than 90% of this lung cancer burden from radon relates to levels below 200 Bq/m^3, and over 40% to levels below 24 Bq/m^3 (fig 2⇓).

The 12.0 Bq/m^3 increase in mean indoor level under scenario 1 was estimated to increase the attributable burden of lung cancer mortality by a peak of around 4700 life years lost and 278 additional deaths per year. Over the 106 year follow-up period, 367 200 fewer life years would be lived by the population, representing about 3500 life years lost per year on average. These impacts would, however, vary over time (table 2⇓). Changes in life years lost in the population would be negligible in the first decade or so after the intervention owing to the lag in lung cancer onset (fig 3⇓) and then increase rapidly, reaching a (sustained) peak after around 40 years and remaining relatively constant thereafter. Mortality impacts would be felt differently in different age groups (fig 4⇓), with the increase in radon related deaths at younger ages reducing the size of the population (and so the number of deaths) in older age. Over the long term, the net effect would be a shift towards deaths at younger ages and a decrease in life expectancy. The average reduction in ventilation related carbon dioxide equivalent emissions for England for this scenario was estimated to be 5.7 Mt CO_2e annually based on the emissions intensity for the current energy supply mix, or 2.3 Mt CO_2e with the energy mix expected by 2030 if the 60% target reduction in carbon intensity is achieved (table 2).

The addition of appropriate purpose-provided ventilation under scenario 2, which mitigates the increase in radon levels, was estimated to be associated with a peak annual radon related lung cancer burden of around 100 additional deaths and almost 1700 life years lost, with 130 900 life years lost over the follow-up period. Savings in carbon dioxide equivalent emissions were correspondingly smaller than in scenario 1. Benefits to health and to carbon emissions were found by incorporating mechanical ventilation and heat recovery in the most airtight dwellings (scenario 3), although scenario 4 shows the importance of ensuring these systems are functioning correctly.

Figure 5⇓ illustrates the trade-off between decreasing ventilation for improved energy efficiency and impact on radon related lung cancer mortality. To maximise ventilation related energy efficiency requires moving dwellings towards the left of the graph where ventilation and hence heat losses are low. However, as the plots for different house archetypes show, exposure to radon increases.[6 37] The shape of the curves indicates a particularly steep rise in the radon burden as ventilation rates approach very low levels below about 0.3 air changes per hour. The trade-off is shown explicitly in the lower plots of fig 5, with radon exposure translated into annual health burden (ignoring the onset time lag) and space heating demand translated into annual greenhouse gas emissions.

Sensitivity analysis

Assumptions about a potentially lower future prevalence of smoking (15% and 10%) indicate that any future radon related adverse health impacts could be smaller than suggested by the estimates presented here, which assume persistence of current smoking rates (table 3⇓). However, assuming no lagged effect of past reductions in smoking prevalence (that is, current lung cancer rates) would increase the impacts presented here. The results indicate that reduction in smoking is a potentially effective strategy for reducing much of the current burden from radon related lung cancer. However, such reductions are not guaranteed, whereas the increases in indoor radon levels are fixed until such time as other interventions are put in place to improve ventilation. In addition, decarbonisation of the energy mix for household energy would progressively erode the benefit of a reduction in ventilation related carbon dioxide equivalent emissions (table 2).

Discussion

This study suggests that energy efficiency interventions that increase the air tightness of dwellings without compensatory purpose-provided ventilation will increase indoor radon concentrations and associated lung cancer risks. The reduced air exchange accompanying efficiency upgrades that meet 2030 GHG abatement targets is likely to increase radon levels by over 50% with an additional annual health burden of close to 5000 life years lost from lung cancer, albeit with a delayed evolution because of the latency of disease. Moreover, fitting extraction fans and trickle ventilators to restore ventilation will help offset the additional burden only if the ventilation related energy efficiency gains are lost. In other words, leaving aside the use of mechanical ventilation and heat recovery, ventilation related improvements in energy efficiency can be achieved only at the expense of additional radon related lung cancer burdens unless there is widespread use of remediation.

Although trends in radon related health burdens may be helped if effective action is taken to reduce smoking prevalence over coming decades, the relative benefit of reduced ventilation on carbon dioxide equivalent emissions is likely to decline over time with progressive decarbonisation of household energy supplies. Even with today's relatively "leaky" housing stock, ventilation related heat losses account for a comparatively modest fraction (around 15%) of all dwelling heat losses(equivalent to around 13 Mt CO_2e of the UK's 600 Mt CO_2e total emissions).[38] Thus the ratio of the positive effects on carbon dioxide equivalent emissions against the detrimental effects on radon related lung cancer will almost certainly become less favourable over time unless clinical treatments become noticeably more effective (which is possible). In addition, our modelling of measures to reduce ventilation under scenario 1 reduces space heating demand for ventilation by 34% (table 2), consistent with 2020 abatement targets, but only half of that needed to achieve 2030 targets: a proportionate reduction in air exchange for the 2030 target would imply substantially greater increases in radon levels and hence risk to health.

Caution is therefore needed to ensure that risks from radon are minimised by appropriate compensatory ventilation systems or cost effective remediation measures. However, a particular challenge for health protection is that the additional burden of radon related deaths from lung cancer is not concentrated in homes with radon above the UK Action Level of 200 Bq/m^3 or even the Target Level of 100 Bq/m^3. Rather, the bulk of additional radon deaths would arise in the millions of homes exposed to levels of radon well below those where conventional remediation is considered cost effective (fig 2).[23 39 40] This is an example of what Rose has called the prevention paradox.[41] Given the (assumed) linear no threshold relation between radon level and lung cancer,[10 30] any upward shift of indoor radon levels across most dwellings has the potential for a genuinely adverse impact at population level; and the same would apply to any other pollutant of indoor origin.

Our evidence also suggests that adding mechanical ventilation and heat recovery in the most airtight dwellings may appreciably reduce indoor radon levels. However, it can only be introduced in the most airtight dwellings (and few current dwellings come close to the required levels of air tightness), pressure differentials may in some circumstances exacerbate radon levels,[42] and, as yet, experience with it has been insufficient to know how well it would work in practice over the long term. Failure of mechanical ventilation and heat recovery systems (through incorrect installation, operation, maintenance, or use) could result in extremely high levels of radon.

Strengths and limitations of this study

The strength of this study has been the ability to combine detailed models of the housing stock, radon levels, and population health to assess a major area of government strategy planned for the coming decades. It is the first study of its kind to model future radon levels and health impacts under climate change mitigation scenarios in such detail and to study the distribution of impacts across the entire housing stock. The models are, of course, somewhat artificial constructs that can never provide entirely accurate representations of such a complex system, and many uncertainties exist. For the purposes of this study we have assumed that people are static. Although individual exposures could change as people relocate, at the population level this should not affect the modelled exposures and health impacts as one household is generally replaced by another: some people may move to more polluted dwellings, whereas others may move to less polluted ones, but the average change in risk of lung cancer remains unaffected. We have incorporated typical occupant behaviour schedules in our models and assumed no changes in behaviour subsequent to the introduction of new technologies. Behaviours will mean some variation in indoor radon levels from dwelling to dwelling (all other things held constant), but our model reflects the current (empirical) distribution of levels, and we consider it reasonable to assume no major change in behaviour from today. Certainly there is little evidence from which to conclude that there would be any change. If future decreases in smoking prevalence are substantial, this could help to ameliorate the adverse impact of increased radon levels, as shown by the sensitivity analyses. Although this provides further reason to encourage smoking cessation, assumption of possible success in smoking reduction is no justification for allowing radon levels to rise. Moreover, decreased ventilation in dwellings will possibly increase second hand exposure to tobacco smoke in households with smokers, a factor that has not been taken into account in our estimations of burden. Finally, we have also not included the full spectrum of potential radon related health outcomes, such as leukaemia,[43] since presently evidence to permit quantification of such impacts is insufficient.

Comparison with other studies

Although uncertainties exist, our model is almost definitely correct about the general direction of change, as the physics dictate that lower air exchange means higher levels of radon,[44] and correct also that energy efficiency achieved by reduced ventilation will result in higher radon related health burdens unless there is specific remediation.[23] Moreover, our estimates of the magnitude of changes in radon levels are broadly in line with previous modelling work,[45 46 47 48] which, as the Swiss Federal Office for Public Health notes, also suggests the potential for a "frequent, sometimes drastic increase" in radon levels after energy efficiency interventions.[49]

Conclusions and policy implications

Our results have important implications for current UK policy related to housing energy efficiency. They should not be interpreted as providing evidence against the desirability of improving home energy efficiency in general. However, reducing ventilation as part of these measures will embed changes for millions of dwellings that may carry substantial detrimental (as well as positive) effects on health while making only a modest contribution to energy efficiency. There is therefore a need for a more careful re-evaluation of how retrofitting of dwellings is carried out to ensure that the potential benefits, including those to health, are not compromised by injudicious air tightening.[50 51] There are different ways of achieving the same end: with regard to radon, a safer strategy might be to place greater emphasis on other measures to reduce energy use, such as improving the conduction properties of dwellings (insulation) and the decarbonisation of the energy supply.

Increasing the energy efficiency of housing is still likely to be a net benefit for health in many cases. This work does not challenge the view that there are generally good reasons for seeking to improve the energy efficiency of housing in England and in many other settings for health as well as for environmental reasons.[45] The caution is in how those energy efficiency improvements are implemented. Radon is just one of several environmental exposures that may be altered by increasing the air tightness of dwellings, some of which, including second hand tobacco smoke and particles of indoor origin, may be adversely affected, whereas others, including indoor temperatures in winter, may be improved.[52] Optimising ventilation strategies for health is therefore more complex if all relevant exposures are taken into account.[53] However, our work highlights the potential problems that may be caused by energy efficiency measures that target heat losses from uncontrolled ventilation. This is a problem that needs much research and debate before undertaking the planned large scale programme of housing investments that may embed health problems for many years to come. For radon at least, caution is needed to ensure that the pursuit of energy efficiency does not precipitate an unwelcome increase in disease burden in the population as a whole. It is also a reminder that all forms of mitigation action have the potential for negative as well as for positive health impacts at population level and need to be carefully planned.

Contributors: The text of this paper was drafted mainly by PW and JM, with contributions from all other authors. PW and JM are guarantors of the work. All authors participated in the design of the study and interpretation of the results. JM, ZC, and PW developed and performed the health impact modelling. CS, PD, BJ, IR, and MD developed and performed the radon modelling and energy calculations. IH analysed the stock data and matched the building models to the stock. BA provided guidance on interpretation of the health model results and sensitivity analysis. All researchers involved in the work had full access to all of the data in the study and can take responsibility for the integrity of the data and the accuracy of the data analysis.

Funding: The research leading to these results received funding from the European Union seventh framework programme FP7/2007-2013 under grant agreement No 265325 (Public health impacts in urban environments of greenhouse gas emissions reduction strategies, PURGE). The funders had no role in study design, in the collection, analysis, and interpretation of data, in the writing of the report, and in the decision to submit the paper for publication. All researchers involved in the work were independent of the funder.

Competing interests: All authors have completed the ICMJE uniform disclosure form at www.icmje.org/coi_disclosure.pdf (available on request from the corresponding author) and declare: no support from any organisation for the submitted work; no financial relationships with any organisations that might have an interest in the submitted work in the previous three years, no other relationships or activities that could appear to have influenced the submitted work.

Ethical approval: Not required.

Data sharing: No additional data available.

Transparency: The lead author affirms that the manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as planned have been explained.

1 HM Government. Climate change act. Stationery Office, 2008.
2 Committee on Climate Change. Building a low-carbon economy—the UK's contribution to tackling climate change. First report. Committee on Climate Change, 2008.
3 Department of Energy and Climate Change. The energy efficiency strategy: the energy efficiency opportunity in the UK. Stationery Office, 2012.
4 Oreszczyn T, Hong S, Ridley I, Wilkinson P. Determinants of winter indoor temperatures in low income households in England. *Energy Build* 2006;38:245-52.
5 Hänninen O, Palonen J, Tuomisto J, Yli-Tuomi T, Seppänen O, Jantunen M. Reduction potential of urban $PM_{2.5}$ mortality risk using modern ventilation systems in buildings. *Indoor Air* 2005;15:246-56.
6 Janssen M. Modeling ventilation and radon in new Dutch dwellings. *Indoor Air* 2003;13:118-27.
7 Nazaroff W. Exploring the consequences of climate change for indoor air quality. *Environ Res Lett* 2013;8:015022.
8 Miles J, Appleton J, Rees D, Green B, Adlam K, Myers A. Indicative atlas of radon in England and Wales. Health Protection Agency, 2007.
9 National Cancer Institute at the National Institutes of Health. Radon and Lung Cancer. 2013. www.cancer.gov/cancertopics/factsheet/Risk/radon
10 Darby S, Hill D, Auvinen A, Barros-Dios J, Baysson H, Bochicchio F, et al. Radon in homes and risk of lung cancer: collaborative analysis of individual data from 13 European case-control studies. *BMJ* 2005;330:223-7.
11 Parkin D, Darby S. Cancers attributable to ionising radiation exposure in the UK in 2010. *Br J Cancer* 2011;105(S2):S57-65.
12 Institute for Sustainability. Retrofit guide 6: improving the building fabric. Institute for Sustainability, 2011.
13 HM Government. The Building Regulations 2010: Approved Document L1A—conservation of fuel and power (2013 edn). DCLG, 2013.
14 Sinnott D, Dyer M. Air-tightness field data for dwellings in Ireland. *Build Environ* 2012;51:269-75.
15 Pan W. Relationships between air-tightness and its influencing factors of post-2006 new-build dwellings in the UK. *Build Environ* 2010;45:2387-99.
16 Dimitroulopoulou S, Crump D, Coward S, Brown V, Squire R, Mann H, et al. Ventilation, air tightness and indoor air quality in homes in England built after 1995. [Contract No: BRE report 477.] Building Research Establishment, 2005.
17 Emmerich S. Validation of multizone IAQ modeling of residential-scale buildings: a review. *ASHRAE Trans* 2001;107:619-28.
18 HM Government. The Building Regulations 2010: Approved Document F—means of ventilation (2010 update). DCLG, 2010.
19 Department for Communities and Local Government. English housing survey. Household report 2008-09. London, 2010.
20 Stephen R. Airtightness in UK dwellings. [Contract No: IP1/00.] Building Research Establishment, 2000.
21 Fang J, Persily A. Computer simulations of airflow and radon transport in four large buildings. National Institute of Standards and Technology, 1995.
22 Gallellia G, Panattoa D, Laia P, Orlandoa P, Rissoa D. Relevance of main factors affecting radon concentration in multi-storey buildings in Liguria (Northern Italy). *J Environ Radioact* 1998;39:117-28.
23 Gray A, Read S, McGale P, Darby S. Lung cancer deaths from indoor radon and the cost effectiveness and potential of policies to reduce them. *BMJ* 2009;338:a3110.
24 American Society of Heating, Refrigeration, and Air-Conditioning Engineers. Fundamentals. ASHRAE, 2009.
25 Kreider J, Rabl A. Heating and cooling of buildings (design for efficiency). McGraw-Hill, 1994.
26 Palmer J, Cooper I. Great Britain's housing energy fact file. Department for Energy and Climate Change, 2011.
27 Committee on Climate Change. Meeting carbon budgets. Third progress report to Parliament. Committee on Climate Change, 2011.

What is already known on this topic

Radon is a radioactive inert gas that enters homes by seepage from the ground

It is the second most important risk factor for lung cancer after smoking and may be responsible for around 1400 cases annually in the United Kingdom

Major improvements to home insulation are expected to reduce energy use and meet climate change mitigation targets

What this study adds

Proposed strategies for reducing greenhouse gas emissions from the housing sector entail interventions that reduce uncontrolled ventilation, which are likely to increase indoor radon levels and associated lung cancer risk

The post-intervention increases in radon for the majority of homes that would contribute most of the additional lung cancer burden are below the threshold at which conventional radon remediation measures are cost effective

The implications of ventilation control on indoor radon levels need to be carefully evaluated before the roll-out of national schemes for improving home energy efficiency

28 Miller B, Hurley J. Life table methods for quantitative impact assessments in chronic mortality. *J Epidemiol Community Health* 2003;57:200-6.
29 Miller B, Hurley J. Comparing estimated risks for air pollution with risks for other health effects. Institute of Occupational Medicine, 2006.
30 Darby S, Hill D, Deo H, Auvinen A, Barros-Dios J, Baysson H, et al. Residential radon and lung cancer—detailed results of a collaborative analysis of individual data on 7148 persons with lung cancer and 14,208 persons without lung cancer from 13 epidemiologic studies in Europe. *Scand J Work Environ Health* 2006;32(suppl 1):1-83.
31 Krewski D, Lubin J, Zielinski J, Alavanja M, Catalan V, Field R, et al. A combined analysis of North American case-control studies of residential radon and lung cancer. *J Toxicol Environ Health A* 2006;69:533-97.
32 Pavia M, Bianco A, Pileggi C, Angelillo I. Meta-analysis of residential exposure to radon gas and lung cancer. *Bull World Health Organ* 2003;81:732-8.
33 Darby S, Hill D, Doll R. Radon: a likely carcinogen at all exposures. *Ann Oncol* 2001;12:1341-51.
34 Health Protection Agency. Radon and public health. HPA, 2009.
35 NHS Information Centre. Statistics on smoking: England, 2011. Health and Social Care Information Centre, Lifestyles Statistics, 2011.
36 Rees D, Bradley E, Green B. Radon in homes in England and Wales: 2010 data review. [Contract No: HPA-CRCE-015.] Health Protection Agency, 2011.
37 Ashok G, Nagaiah N, Prasad NS. Indoor radon concentration and its possible dependence on ventilation rates and flooring type. *Radiat Prot Dosimetry* 2012;148:92-100.
38 Hamilton I, Davies M, Ridley I, Oreszczyn T, Hong S, Barratt M, et al. The impact of the 'take back' effect in UK domestic stock modeling: health impacts and CO_2 emissions. *Build Serv Eng Res Technol* 2011;32:85-98.
39 Denman A, Coskeran T, Phillips P, Crockett R, Tornberg R, Groves-Kirkby C. Lowering the UK domestic radon action level to prevent more lung cancers□is it cost-effective? *J Radiol Prot* 2008;28:61-71.
40 Kennedy C, Gray A, Denman A, Phillips P. The cost-effectiveness of residential radon remediation programmes: assumptions about benefits stream profiles over time. *J Environ Radiact* 2002;59:19-28.
41 Rose G. Strategy of prevention: lessons from cardiovascular disease. *BMJ* 1981;282:1847-51.
42 Arvela H, Holmgren O, Reisbacka H, Vinha J. Review of low-energy construction, air tightness, ventilation strategies and indoor radon: results from Finnish houses and apartments. *Radiat Prot Dosimetry* . 2013. Published online 14 Nov.
43 Řeřicha V, Kulich M, Řeřicha R, Shore D, Sandler D. Incidence of leukemia, lymphoma, and multiple myeloma in Czech uranium miners: a case-cohort study. *Environ Health Perspect* 2007;114:818-22.
44 Lugg A, Probert D. Indoor radon gas: a potential health hazard resulting from implementing energy-efficiency measures. *Appl Energy* 1997;56:93-196.
45 Wilkinson P, Smith K, Davies M, Adair H, Armstrong B, Barrett M, et al. Public health benefits of strategies to reduce greenhouse-gas emissions: household energy. *Lancet* 2009;374:1917-29.
46 Briggs D, Denman A, Gulliver J, Marley R, Kennedy C, Philips P, et al. Time activity modelling of domestic exposures to radon. *J Environ Manage* 2003;67:107-20.
47 Hunter N, Muirhead CR, Miles JC, Appleton JD. Uncertainties in radon related to house-specific factors and proximity to geological boundaries in England. *Radiat Prot Dosimetry* 2009;136:17-22.
48 Nero A, Boegel M, Hollowell C, Ingersoll J, Nazaroff W, Revzan K. Radon and its daughters in energy-efficient buildings. Lawrence Berkeley National Laboratory, 1980.
49 Swiss Federal Office for Public Health. Energy efficiency and radon website. 2013. www.bag.admin.ch/themen/strahlung/00046/11594/?lang=en
50 Davies M, Oreszczyn T. The unintended consequences of decarbonising the built environment: a UK case study. *Energy Build* 2012;46:80-5.
51 Manuel J. Avoiding health pitfalls of home energy-efficiency retrofits. *Environ Health Perspect* 2011;119:A76-9.
52 Bone A, Murray V, Myers I, Dengel A, Crump D. Will drivers for home energy efficiency harm occupant health? *Perspect Public Health* 2010;130:233-8.
53 Das P, Chalabi Z, Jones B, Milner J, Shrubsole C, Davies M, et al. Multi-objective methods for determining optimal ventilation rates in dwellings. *Build Environ* 2013;66:72-81.

Accepted: 6 December 2013

Cite this as: *BMJ* 2014;348:f7493

Tables

Table 1| Summary statistics of indoor radon concentrations for all scenarios

Scenarios	Radon concentration (Bq/m^3)			Percentage >200 Bq/m^3
	Mean	Median	95th centile	
Present (baseline)	21.2	12.5	73.3	0.6
Scenario 1 (air tightness)	33.2	19.5	121.2	2.0
Scenario 2 (air tighteness+purpose-provided ventilation)	25.5	13.9	94.6	1.2
Scenario 3 (as for scenario 2+MVHR)	19.6	11.1	69.8	0.5
Scenario 4 (as for scenario 3+10% failures in MVHR)	21.8	11.8	85.3	0.6

MVHR=mechanical ventilation and heat recovery systems.

Table 2| **Modelled health impacts and estimated changes in stock annual space heating demand and greenhouse gas (GHG) emissions for different assumptions of decarbonisation of space heating energy supply**

Scenarios	Change in life years lived by population*: 0-20 years	0-50 years	Over follow-up period	Change in stock annual space heating demand for ventilation (TWh)	Change in stock annual GHG emissions (Mt CO_2e)†: No further decarbonisation	Assuming 34% decarbonisation (2020 target)	Assuming 60% decarbonisation (2030 recommended target)
Scenario 1 (air tightness)	–5200	–121 000	–367 200	–27	–5.6	–3.7	–2.2
Scenario 2 (air tightness+purpose-provided ventilation)	–1800	–43 100	–130 900	–15	–3.2	–2.1	–1.3
Scenario 3 (as for scenario 2+MVHR)	4000	21 500	54 000	–22	–4.5	–3.0	–1.8
Scenario 4 (as for scenario 3+10% failures in MVHR)	–300	–7000	–21 300	–22	–4.5	–3.0	–1.8

Mt CO_2e=megatonnes of carbon dioxide equivalent; TWh=terawatt hour; g/kWh=grammes per kilowatt hour; MVHR=mechanical ventilation and heat recovery systems.

*Figures rounded to nearest 100; negative figures indicate loss of life years.

†Assuming current carbon intensity of 208 g/kWh(38).

Table 3| **Sensitivity of health impacts to smoking prevalence and lung cancer mortality rate**

	Health impact (change in life years over follow-up period)*					
	Current (2009) lung cancer mortality			50% reduction from current (2009) lung cancer mortality		
	Assumed smoking prevalence			Assumed smoking prevalence		
Scenarios	**21% (current)**	**15%**	**10%**	**21% (current) (base case)**	**15%**	**10%**
Scenario 1 (air tightness)	–733 800	–558 700	–412 900	–367 200	–279 600	–206 600
Scenario 2 (air tightness+purpose-provided ventilation)	–261 700	–199 300	–147 200	–130 900	–99 700	–73 600
Scenario 3 (as for scenario 2+MVHR)	108 100	82 300	60 800	54 000	41 100	30 400
Scenario 4 (as for scenario 3+10% failures in MVHR)	–42 500	–32 400	–23 900	–21 300	–16 200	–12 000
Approximate % change in health impact relative to base case	100	52	12	0 (base case)	–24	–44

MVHR=mechanical ventilation and heat recovery systems.

*Figures rounded to nearest 100; negative figures indicate loss of life years.

Figures

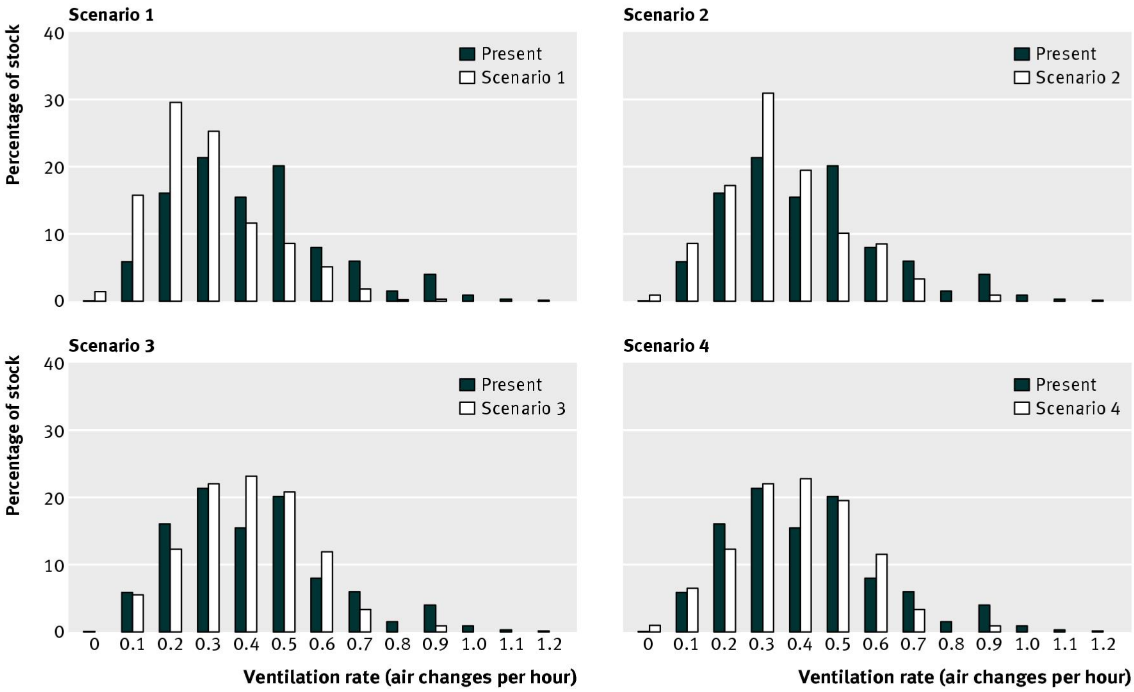

Fig 1 Modelled present day and future ventilation rate distributions of English housing stock. Scenario 1=air tightness; scenario 2=air tightness+purpose-provided ventilation; scenario 3=as for scenario 2+mechanical ventilation and heating recovery (MVHR); scenario 4=as for scenario 3+10% failures in MVHR

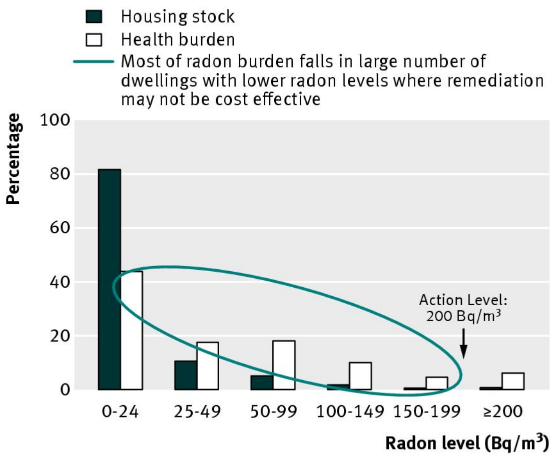

Fig 2 Proportions of current housing stock and attributable burden of radon related lung cancer mortality for different levels of radon

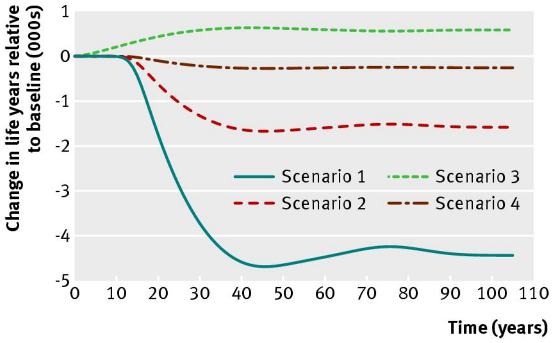

Fig 3 Change in life years lived in population (relative to baseline) over time for each scenario. Negative figures indicate loss of life years. Scenario 1=air tightness; scenario 2=air tightness+purpose-provided ventilation; scenario 3=as for scenario 2+mechanical ventilation and heat recovery (MVHR); scenario 4=as for scenario 3+10% failures in MVHR

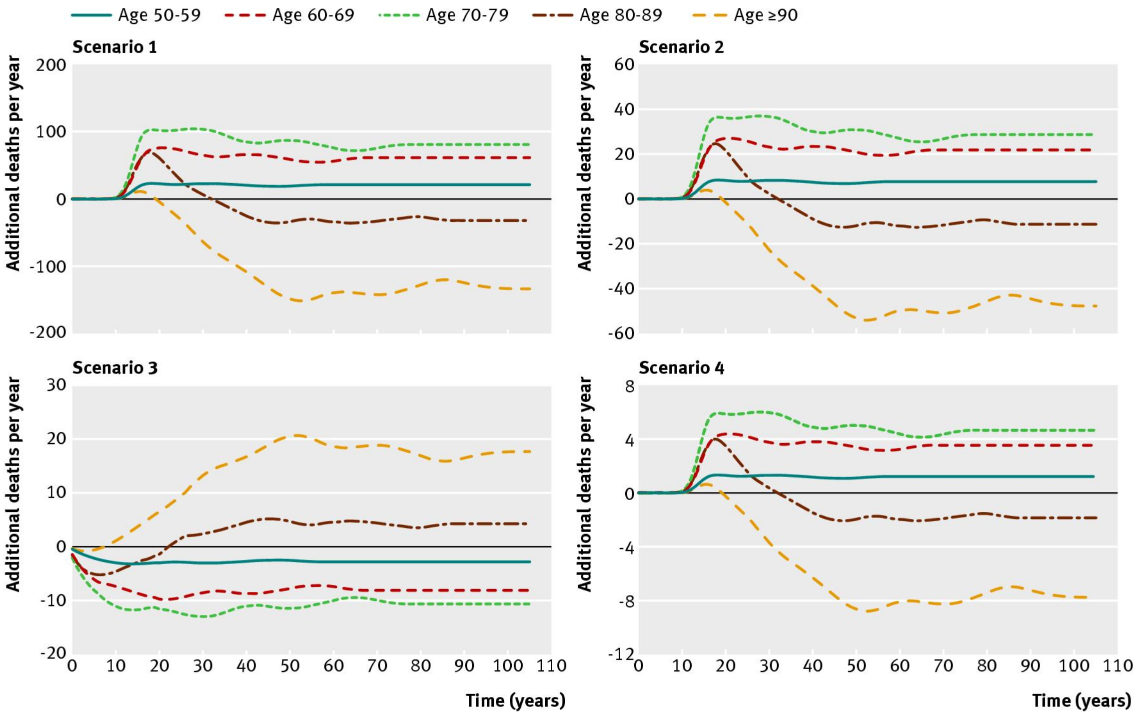

Fig 4 Additional deaths per year (relative to baseline) over time for each scenario and for different age groups. Scenario 1=air tightness; scenario 2=air tightness+purpose-provided ventilation; scenario 3=as for scenario 2+mechanical ventilation and heat recovery (MVHR); scenario 4=as for scenario 3+10% failures in MVHR. Note changes of scale on y axes

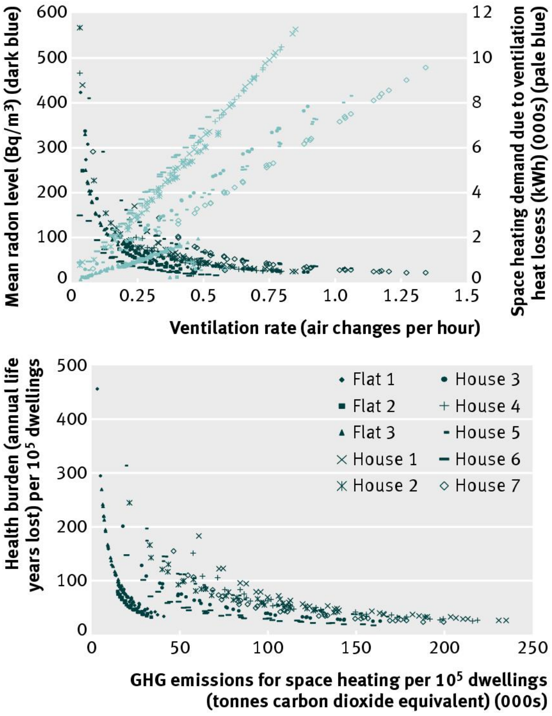

Fig 5 Mean radon level and space heating demand due to ventilation heat losses for the English housing stock plotted against ventilation rate, and current attributable health burden (annual life years lost assuming no lag) compared with annual greenhouse gas (GHG) emissions for space heating per 10^5 dwellings