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What should the ventilation objectives be for retrofit energy efficiency interventions of dwellings?

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Abstract

Major energy efficiency refurbishment of the UK housing stock is needed to help attain emission reduction targets of greenhouse gases. Such measures typically entail some planned or incidental reduction of uncontrolled ventilation in dwellings. This paper examines the trade-offs for health and sustainability objectives of typical retrofit refurbishments in UK homes. While reducing ventilation can help protect against the ingress of harmful pollutants from the outdoor air, our results demonstrate that reducing permeability to low levels, without additional purpose-provided ventilation, is likely to lead to substantial increases in pollutants derived from indoor sources, including indoor-generated particles, radon, and environmental tobacco smoke. The monetized equivalent cost of the health dis-benefits associated with these exposures may exceed the potential benefits of reducing energy costs and greenhouse gas emissions.

Practical application

Reducing uncontrolled ventilation of dwellings helps to improve energy efficiency and can protect against the ingress of pollutants from the outdoor environment. However, simulation studies suggest that at high degrees of airtightness (very low permeability) there is a potentially steep rise in pollutants of indoor origin, whose adverse effects on health may outweigh the benefits of reduced energy use, lower CO_2 emissions, and protection against outdoor pollution. Though the optimal permeability level for a given dwelling will vary with local circumstances, considerations of health protection suggest the need to avoid reducing permeability to low levels.

1. Introduction

Residential emissions of greenhouse gases (GHGs) account for just under 17% of the UK's total.[1] They are an important target for emissions reduction because of the relative tractability of energy efficiency and other GHG-sparing measures in this sector, and because of the potential ancillary benefits of such measures for the alleviation of fuel poverty, household energy insecurity, and winter-and cold-related mortality and morbidity. Substantial investments are needed and planned for the coming decades, with primary emphasis on energy efficiency achieved through better insulation of the fabric (the walls, roof, and floor) of dwellings and tighter control of ventilation.[2, 3]

We have previously reported potential adverse consequences for indoor radon concentrations and health of reducing uncontrolled ventilation in dwellings.[4] Similar arguments apply to other pollutants derived from indoor sources, notably particles of indoor origin, environmental (second-hand) tobacco smoke and those associated with mould growth, although reduced air exchange would have a positive benefit in protecting against the ingress into the home of particles and other pollutants from the outdoor air.[5] Moreover, reduction of ventilation-related heat losses is likely to make only a modest contribution to the overall energy efficiency improvement of existing dwellings, and to the increase in indoor temperatures.[6] Thus, there is a potential trade-off with ventilation control between the positive effects of improving energy efficiency and protecting against outdoor pollutants on the one hand, and the adverse consequences of increases in pollutants derived from indoor sources on the other.

In previous work, we described an optimization approach for determining ideal ventilation rates of dwellings, accounting for their energy use and impact on health.[7] This paper further explores the risk/benefit trade-offs through a set of simulation studies that indicate the nature of the transition towards dominant adverse health effects as dwelling ventilation is reduced.

2. Methods

We modelled indoor levels of several contaminants, energy demand for space heating, and associated GHG emissions in a typical English detached house with three bedrooms over permeability values in the range 1 to 40 $m^3 m^{-2} hr^{-1}$ at 50 Pa, and estimated the associated health burdens using life table methods.

2.1 Indoor exposures

The validated multizone pollutant model CONTAM[8 9 10] was used to estimate average indoor levels of particles of maximum aerodynamic diameter of 2.5 µm ($PM_{2.5}$) derived from *outdoor* sources, $PM_{2.5}$ derived from *indoor* sources, environmental tobacco smoke, and radon. Indoor source emission rates were based on published estimates[11 12] and a mean ambient $PM_{2.5}$ concentration of 13 µg m^{-3} was used to represent an urban area, based on data from the Automatic Urban and Rural Network (AURN) and the London Air Quality Network (LAQN).[13] Fabric infiltration was modelled via two openings (cracks) in each wall. Operational characteristics of extract fans and trickle vents were matched to UK industry norms to comply with minimum whole house ventilation rates required by Approved Document F (HM Government, 2010).[14] Model inputs for radon and $PM_{2.5}$ are described in greater detail elsewhere.[4 15] For radon, separate models for low, medium, and high radon exposure areas were constructed by multiplying the modelled exposures by factors determined by calibration against observed data. For $PM_{2.5}$, a range of illustrative annual average outdoor concentrations were modelled to represent houses in locations with different levels of ambient air pollution. For environmental tobacco smoke, indoor levels were normalised to give a mean exposure of 1 across the housing stock (full stock model not presented here).

Models were constructed over a range of permeabilities at selected intervals from 3 $m^3 m^{-2} hr^{-1}$ (very air tight) to 40 $m^3 m^{-2} hr^{-1}$ (very 'leaky') and for four different ventilation strategies (no purpose-provided ventilation, trickle vents, extract fans, trickle vents and extract fans). To obtain estimates over the full permeability range, polynomial functions were fitted to the results of the simulations for both the indoor-generated pollutants and outdoor-generated $PM_{2.5}$. A stock-weighted average of the different ventilation types for each pollutant was calculated based on data from the 2010 English Housing Survey.[16]

2.2 Energy use and CO_2 emissions

Space heating demand due to ventilation heat losses for the detached house was estimated over the range of permeabilities using the standard degree-hour method assuming a heating efficiency of 77%.[17-19] Separate polynomial functions were fitted for each of the four ventilation strategies and a stock weighted average was calculated. The corresponding GHG emissions (as carbon dioxide equivalent, CO_2e) were estimated by multiplying the energy demand by the carbon intensity of the UK's energy supply (248.8 g kWh^{-1}).[20 21]

2.3 Health burden

Mortality associated with the estimated exposures over the range of dwelling permeabilities was calculated for health outcomes with the strongest epidemiological evidence (Table 1).

The burden of mortality (per 100 000 population) was modelled using a multiple decrement life table (i.e. each cause of death included in a single life table), adapted from the IOMLIFET model.[22] The life table models the pattern of survival in the population over time based on age-specific death rates. Changes in these rates (due to changes in the environmental exposures) affect the life expectancy of the population. We used non-overlapping causes of mortality: for example, deaths due to cerebrovascular accident were excluded from cardiopulmonary deaths to avoid double counting. Separate life tables for males and females were set up using 2010 population and mortality data for England and Wales from the Office for National Statistics (ONS). Where different exposures affected the same outcome, risks were assumed to be multiplicative. Environmental tobacco smoke was assumed to affect only non-smokers living with smokers (16.6% according to the 2010 English Housing Survey) and $PM_{2.5}$ risks were scaled for time spent indoors at home (53%).[23]

The burden calculation was performed by applying the exposure-response functions (i) to the age-specific deaths to estimate the expected additional deaths at each age, and (ii) to the life table to estimate remaining life expectancy at each age. The deaths at each age were then multiplied by the remaining life expectancy to estimate the total years of life lost (YLL) associated with those deaths, which were summed over all ages.

2.4 Costs

Costs associated with health impacts, energy use and CO_2 emissions were calculated. These were based on (i) the monetized cost of YLL using a valuation of £30 000 per life year[24], (ii) the social cost of carbon dioxide equivalent (CO_2e) emissions, represented by illustrative assumed future tariffs of £15 and, as an extreme value, £75 per tonne[25], and (iii) the direct space heating-related fuel costs at an assumed tariff of £0.05 per kilowatt hour (kWh).

3. Results

Figure 1 illustrates the results of the simulations of indoor concentrations of the four key pollutants in relation to dwelling permeability: $PM_{2.5}$ (due to both indoor and outdoor sources), environmental tobacco smoke, and radon. For particles derived from outdoor sources there is a curvilinear increase in concentrations with increasing permeability, with the increase in concentrations getting progressively less at higher permeabilities. This pattern of course reflects the greater ingress of outdoor particle pollution with increasing leakiness of the dwelling. For the other three (indoor-generated) pollutants, the functions have an approximately exponential decay form with concentrations highest at very low levels of permeability, initially falling rapidly with increasing permeability but settling into much more gradual declines in concentrations with increasing permeability above around 15 $m^3 m^{-2} hr^{-1}$. For all indoor-generated pollutants, dwellings with trickle vents, and especially extract fans or both, had lower levels of pollutants than dwellings with neither. These plots indicate a relatively critical influence of dwelling permeability on the concentration of indoor pollutants towards very low levels of permeability. For particulate pollution from outdoor sources, however, dwellings without purpose-provided ventilation are most protective.

Figure 2 shows the effect of permeability on space heating-related energy demand, carbon dioxide emissions and YLL due to indoor pollutant exposure. Unsurprisingly, in Figure 2[A] there is a broadly linear increase in space heating energy demand as permeability rises (due to the need to heat increasingly large volumes of air per hour), and also of the related GHG emissions. The gradient of the rise in heating-related CO_2 emissions with permeability is dependent upon the carbon intensity of the energy sources used for space heating and, as illustrated in Figure 2[B], declines proportionately with increasing decarbonization (eventually yielding a flat line of zero gradient at 100% decarbonization). The curves for YLL per 100 000 population per year (Figure 2[C]) reflect the net effect on health of all the modelled pollutants in combination, and again take the form of an approximately exponential function. There are steep declines in the health burden as permeability increases from very low levels of permeability but quickly levelling off to a more gradual decline at higher levels of permeability above around 15 $m^3 m^{-2} hr^{-1}$. The shape of the curve reflects the dominance of the effect of the indoor pollutants (particles of indoor origin, environmental tobacco smoke, and radon) over that of particles derived from outdoor sources. As Figure 2[C] illustrates, varying the assumption of the concentration of outdoor particles ($PM_{2.5}$) shifts the curve (of YLL vs. permeability) upwards or downwards in proportion to the outdoor $PM_{2.5}$ concentration. The figure demonstrates how the protective effect of the building envelope against outdoor particles would become less important if ambient air pollution levels were to be reduced in the future.

Figure 3 illustrates, for an ‘average’ dwelling and ventilation strategy, the annualized monetary costs (relating to health, energy and CO_2e emissions) in relation to dwelling permeability. When only health impact (YLL) costs are included, the monetized cost of the adverse health effects of air pollutants (which are heavily influenced by exposure to indoor-generated pollutants) continues to decline with increasing permeability, albeit very gradually at higher permeability levels. The addition of monetized social costs of carbon dioxide emissions, and especially of direct fuel costs, superimpose an approximately linear increase in costs with permeability on the YLL curve. The resulting functions show a more-or-less well-defined unique minimum value of costs. With higher tariffs for the social cost of carbon dioxide (and/or inclusion of direct fuel costs), the minimum cost permeability lies in the range of 3 to 7 $m^3 m^{-2} hr^{-1}$. With social costs of carbon dioxide emissions included at relatively low values, the minimum cost permeability lies at much higher permeability levels.

Indeed, even at £15 per tCO_2e (close to the higher estimate for the social costs of carbon at 2014 valuations[25]), the minimum cost point is above 40 $m^3\ m^{-2}\ hr^{-1}$.

4. Discussion

The simulations of indoor pollutant levels and resultant impacts on health at different levels of dwelling permeability illustrate the potential importance of ventilation in protecting health and the potential trade-off between health objectives on the one hand and those of improving energy efficiency and reducing carbon dioxide emissions on the other.

Although based on quite specific sets of assumptions and taking average values for a range of indoor pollutants, the primary conclusion seems clear: that reducing permeability of dwellings to low levels without additional purpose-provided ventilation is likely to have net adverse effects on human health, and that the monetized costs of those negative health effects reach a point where they exceed the potential (monetized) benefits in terms of reduced energy cost and CO_2 emissions. The point of optimal permeability (which minimizes *net* costs) will vary from dwelling to dwelling and depend on the assumptions made about the value of human life, the social costs of carbon dioxide and costs of fuel. In circumstances where the carbon savings and/or their monetized costs are small, the point of optimal permeability may not be clearly defined, or indeed the net cost function may continue gradually to decline at higher and higher permeability levels; where fuel costs and the social costs of carbon are high, the point of optimal permeability appears relatively well-defined. But for all net cost curves, a point is reached at which the transition to dominant adverse effects on health turns into a steep rise in net costs at lower and lower permeability levels. Within the assumptions used for our simulations, this critical point of transition appears to occur at permeability values below around 7 $m^3\ m^{-2}\ hr^{-1}$. Below this level, the adverse consequences for health of exposure to pollutants of indoor origin rise rapidly and ever more steeply, while the net cost function typically shows a shallower rate of change at permeability levels to the right of this point. Thus, there is a relatively severe penalty for reducing ventilation too much (below the point of 'critical transition'), and relatively minor penalty, or in some circumstances even a net benefit, of erring in the other direction towards greater permeability. This observation suggests an important point of principle, namely that there is a target lower limit of permeability/ventilation which it would be unsafe to reduce further, while some latitude might be allowed for higher levels of ventilation. (There are relatively marginal changes in the balance of risks and benefits as permeability increases towards higher levels.)

The exact location of this critical point of transition will not be the same for all dwellings and households and will of course also be influenced by which costs and benefits are included in the assessment. It is worth noting that the analyses presented here did not include the capital costs of investments to achieve lower levels of permeability (which would in part offset the net gain in energy cost savings to the householder at lower permeability), nor did they include the potential impacts of improved winter temperatures on health, though these are likely to be small.[26] It is also worth noting that the potential adverse consequences of increasing concentrations of pollutants of indoor origin at low permeability levels could, in theory, be avoided by use of mechanical ventilation and heat recovery (MVHR) systems, although it would be difficult to achieve the level of permeability required for MVHR installation in many existing dwellings. (In any case, there is evidence to suggest MVHR systems may not necessarily improve indoor air quality due to ineffective use and poor maintenance.[27]) It is also noteworthy that if energy sources are decarbonized over time, the CO_2 benefits of ventilation control will also diminish, as would benefits from the reduced ingress of outdoor pollution as outdoor $PM_{2.5}$ levels will also be lower. These factors will tend to reduce the benefits of lower permeability levels.

It is also important to be aware that our simulations have entailed many assumptions and examined only a limited set of permutations of dwelling and other characteristics. Results are likely to vary appreciably with such factors as dwelling type, outdoor pollution concentrations and soil types (which may influence radon emissions), as well as whether the household contains any smokers. We also made an important but challengeable assumption that particles of indoor origin are equally toxic as those derived from the outdoor air, an assumption that has obvious bearing on the relative impact of the reduced ingress of pollution from outside and that of pollutants derived from indoor sources when dwellings are tightened. The net costs and benefits were also limited to the monetized cost of health impact, the social costs of CO_2 emissions and direct fuel costs, but excluded other potential benefits and costs, including, for example, changes in health care treatment or social care costs.

5. Conclusions

In conclusion, our analysis demonstrates potential trade-offs for health with the reduction of uncontrolled ventilation of dwellings in pursuit of energy efficiency objectives. While such reduction may make a modest contribution to improving energy efficiency and will help protect against outdoor pollutants, there is a danger, especially at relatively low levels of permeability, of substantial increases in pollutants derived from indoor sources. Such increases may carry appreciable dis-benefits for health. The level of permeability at which there is ‘optimal’ trade-off between such dis-benefits and the positive effects on energy efficiency, indoor temperature and protection against outdoor pollutants, will vary from dwelling to dwelling, but based on the limited evidence of our current simulations, it would seem prudent to avoid measures aimed at reducing permeability and hence air exchange to very low levels.

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References

1. DECC. 2013 UK Greenhouse Gas Emissions. Provisional Figures and 2012 UK Greenhouse Gas Emissions. Final Figures by Fuel Type and End-User. London, UK: Department of Energy and Climate Change, 2014.
2. DECC. The UK Low Carbon Transition Plan: National Strategy for Climate and Energy. London, UK: Department of Energy and Climate Change, 2009.
3. UK CCC. Fourth Carbon Budget. London, UK: UK Committee on Climate Change, 2010.
4. Milner J, Shrubsole C, Das P, Jones B, Ridley I, Chalabi Z, Hamilton I, Armstrong B, Davies M, Wilkinson P. Home energy efficiency and radon related risk of lung cancer: modelling study. Bmj 2014; 348: f7493
5. Hänninen OO, Palonen J, Tuomisto JT, Yli-Tuomi T, Seppänen O, Jantunen MJ. Reduction potential of urban $PM_{2.5}$ mortality risk using modern ventilation systems in buildings. Indoor Air 2005; 15: 246-56
6. Oreszczyn T, Hong S, Ridley I, Wilkinson P. Determinants of winter indoor temperatures in low income households in England. Energy and Buildings 2006; 38: 245-52
7. Das P, Chalabi Z, Jones B, Milner J, Shrubsole C, Davies M, Hamilton I, Ridley I, Wilkinson P. Multi-objective methods for determining optimal ventilation rates in dwellings. Building and Environment 2013; 66: 72-81
8. Emmerich SJ. Validation of multizone IAQ modeling of residential-scale buildings: a review. ASHRAE Transactions 2001; 107(2): 1-10
9. Haghighat F, Li H. Building airflow movement - validation of three air flow models. Journal of Architectural and Planning Research 2004; 21: 331-49
10. Walton GN, Dols WS. CONTAM 2.4c User Guide and Program Documentation. NISTIR 7251. Gaithersburg, MD, USA: National Institute of Standards and Technology, 2006.
11. Fang J, Persily A. Computer smulations of airflow and radon transport in four large buildings. Gaithersburg, MD, USA: National Institute of Standards and Technology, 1995.
12. Ozkaynak H, Xue J, Spengler J, Wallace L, Pellizzari E, Jenkins P. Personal exposure to airborne particles and metals: results from the Particle TEAM study in Riverside, California. J Expo Anal Environ Epidemiol 1996; 6(1): 57-78
13. LAQN. London Air Quality Network. Available at: http://www.londonair.org.uk/london/asp/datadownload.asp 2010.
14. DCLG. Approved Document F: Ventilation (2010 Ed). London, UK: The Stationery Office, 2010.
15. Shrubsole C, Ridley I, Biddulph P, Milner J, Vardoulakis S, Ucci M, Wilkinson P, Chalabi Z, Davies M. Indoor $PM_{2.5}$ exposure in London's domestic stock: Modelling current and future exposures following energy efficient refurbishment. Atmospheric Environment 2012; 62(0): 336-43
16. DCLG. English Housing Survey. Household Report 2010-2011. London, UK: Department for Communities and Local Government, 2012.

17. ASHRAE. Fundamentals. Atlanta, GA, USA: American Society of Heating, Refrigeration, and Air-Conditioning Engineers, 2009.
18. Kreider J, Rabl A. Heating and Cooling of Buildings (Design for Efficiency). New York, NY, USA.: McGraw-Hill; 1994.
19. Palmer J, Cooper I. Great Britain's Housing Energy Fact File. London, UK: Department for Energy and Climate Change, 2011.
20. DECC. Energy Consumption in the UK. London, UK: Department of Energy and Climate Change, 2014.
21. Defra. 2013 Government GHG Conversion Factors for Company Reporting: Methodology Paper for Emission Factors. London, UK: Department for Environment, Food & Rural Affairs, 2013.
22. Miller BG, Hurley JF. Life table methods for quantitative impact assessments in chronic mortality. Journal of Epidemiology & Community Health 2003; 57(3): 200-6
23. Kornartit C, Sokhi RS, Burton MA, Ravindra K. Activity pattern and personal exposure to nitrogen dioxide in indoor and outdoor microenvironments. Environ Int 2010; 36(1): 36-45
24. Devlin N, Parkin D. Does NICE have a cost-effectiveness threshold and what other factors influence its decisions? A binary choice analysis. Health Economics 2004; 13: 437-52
25. DECC. Updated Short-Term Traded Carbon Values used for UK Public Policy Appraisal. London, UK: Department of Energy and Climate Change, 2013.
26. Milner J, Chalabi Z, Wilkinson P, Armstrong B, Cairns J, Duffy S, Hajat S, Jones L, Petticrew M, Scovronik N. Evidence Review and Economic Analysis of Excess Winter Deaths. Review 2: Interventions and Economic Studies. London, UK: Report for the National Institute for Health and Care Excellence (NICE), 2014.
27. Balvers J, Bogers R, Jongeneel R, van Kamp I, Boerstra A, van Dijken F. Mechanical ventilation in recently built Dutch homes: technical shortcomings, possibilities for improvement, perceived indoor environment and health effects. Architectural Science Review 2012; 55: 4–14
28. Pope CA, 3rd, Burnett RT, Thun MJ, Calle EE, Krewski D, Ito K, Thurston GD. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. Jama 2002; 287(9): 1132-41
29. Pope CA, 3rd, Burnett RT, Thurston GD, Thun MJ, Calle EE, Krewski D, Godleski JJ. Cardiovascular mortality and long-term exposure to particulate air pollution: epidemiological evidence of general pathophysiological pathways of disease. Circulation 2004; 109(1): 71-7
30. Lee PN, Forey BA. Environmental tobacco smoke exposure and risk of stroke in nonsmokers: a review with meta-analysis. Journal of Stroke and Cerebrovascular Diseases 2006; 15(5): 190-201
31. Law MR, Morris JK, Wald NJ. Environmental tobacco smoke exposure and ischaemic heart disease: an evaluation of the evidence. Bmj 1997; 315(7114): 973-80

32. Darby S, Hill D, Auvinen A, Barros-Dios JM, Baysson H, Bochicchio F, Deo H, Falk R, Forastiere F, Hakama M, Heid I, Kreienbrock L, Kreuzer M, Lagarde F, Makelainen I, Muirhead C, Oberaigner W, Pershagen G, Ruano-Ravina A, Ruosteenoja E, Rosario AS, Tirmarche M, Tomasek L, Whitley E, Wichmann HE, Doll R. Radon in homes and risk of lung cancer: collaborative analysis of individual data from 13 European case-control studies. Bmj 2005; 330(7485): 223

Tables

Table 1. Modelled exposure-outcome pathways and sources.

ɜxposure	ɔutcome	re-response ship	
	ɪulmonary mortality	er 10 µg m^{-3}	: al. (2004; 2002)[28 29]
	ɪncer mortality	er 10 µg m^{-3}	ɪve)
mental tobacco	ɔvascular accident y	in same dwelling as)	l Forey (2006)[30]
	dial infarction y	in same dwelling as)	al. (1997)[31]
	ɪncer mortality	r 100 Bq m^{-3}	ɪt al. (2005)[32]

Figure captions

Figure 1. Modelled concentrations of indoor pollutants vs. dwelling permeability for detached dwelling under four different ventilation strategies and stock weighted average. [A] $PM_{2.5}$ from outdoor sources, [B] $PM_{2.5}$ from indoor sources, [C] environmental tobacco smoke and [D] radon. NOTE = no trickle vents or extract fans; T = trickle vents only; E = extract fans only; TE = trickle vents and extract fans.

Figure 2. [A] Energy demand for space heating vs. permeability for detached dwelling under four different ventilation strategies and stock weighted average,[B] space heating-related CO_2 emissions vs. permeability for detached dwelling for current energy supply carbon intensity and for different levels of decarbonization, and [C] years of life lost per 100,000 population vs. permeability for detached dwelling at different outdoor $PM_{2.5}$ concentrations. NOTE = no trickle vents or extract fans; T = trickle vents only; E = extract fans only; TE = trickle vents and extract fans.

Figure 3. Curves of annualized costs for detached dwelling relating to monetized impact on health, social cost of CO_2-equivalent emissions and energy costs vs. dwelling permeability. Red curve: monetized cost of years of life lost (YLL) attributable to indoor pollutants only; green curves: YLL + social cost of CO_2e emissions at £15 or £150 per tonne; grey curves: YLL + social cost of CO_2e at £15 and £150 per tCO_2e + direct fuel costs at an assumed tariff of £0.05 per kWh.