

THE FUTURE OF
**INDOOR AIR QUALITY
IN UK HOMES**
AND ITS
IMPACT ON HEALTH

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SUMMARY

The UK Government is committed, by law, to an 80% reduction in carbon emissions by 2050. 30% of present UK carbon emissions relate to domestic buildings and whilst there are building regulations in place to reduce domestic carbon emissions, it is widely agreed that these will be insufficient to meet the required 2050 targets and that further government regulation and guidance will be required.

Existing building regulations enforce improved air-tightness on all new homes and sample air permeability testing to help ensure that this is achieved in practice. However, building regulations have not taken into consideration the adverse impact of improved air-tightness and increased energy efficiency on indoor air quality (IAQ) and the health of occupants.

It is evident that a variety of airborne pollutants exist in homes, many of which are likely to be at their highest levels in newly built and newly-refurbished homes. The trend towards greater levels of air tightness will exacerbate pollutant levels in addition to elevated humidity levels during drying-out periods for new or refurbished dwellings. This reinforces the need for the design, construction and commissioning of buildings to be undertaken with IAQ firmly in mind.

In addition to new homes, it is estimated that about 87% of existing domestic buildings in the UK will still exist in 2050, requiring approximately 22 million homes to be 'retrofitted' with energy efficiency improving measures to meet carbon emission obligations.

It is well documented that poor IAQ has significant impact on people's health and loss of life years. Based on a review of a number of international studies, there is little doubt that poor IAQ is connected with a range of undesirable health effects, such as allergic and asthma symptoms, lung cancer, chronic obstructive pulmonary disease, airborne respiratory infections and cardiovascular disease. With the expected increase in air tightness for UK dwellings, it is anticipated that indoor air quality will generally become poorer, resulting in an increase in the number of cases of health symptoms related to poorer indoor environment quality. This is expected to mostly affect individuals prone to such health conditions and those who spend most time indoors, including young mothers, children and the elderly.

This report surveys current knowledge on the effect of indoor air pollution on people's health and projects how increased levels of energy efficiency and air-tightness of UK dwellings, to meet emissions targets, will impact on pollution levels and health up to 2050 if there is no additional IAQ intervention, over and above existing requirements. Key projections include:

- an 80% increase in asthma sufferers from current levels
- TVOC concentrations up to 60% above WHO 24 hour limits
- NO₂ concentrations up to 30% above WHO annual limits

This report concludes and recommends that:

1. Existing building regulations have the potential to increase indoor pollutant levels equivalent to the upper end of (and in some cases well above) World Health Organisation recommended limits.
2. There should be a legal requirement for new homes, and guidance for retrofitted homes, to have an air exchange rate of at least 0.5/hour, to help protect human health.
3. The standardised fitting of effective continuous mechanical ventilation, preferably with heat recovery (MVHR), is the most cost-effective solution for achieving this exchange rate whilst satisfying energy efficiency requirements

Any future building regulations to reduce carbon emissions should be accompanied by government regulation to ensure effective and efficient design, installation, maintenance and operation of MVHR systems to reduce the impact upon human health.

1. INTRODUCTION

In the 1950s, air pollution caused by industry - mainly suspended particles and sulphur dioxide (SO₂) - was clearly identified as being responsible for increases in respiratory and cardiovascular mortality. Since then the industrialised countries have adopted a series of basic regulatory measures which have led to a significant reduction of this type of pollution and impact on human health. However, air pollution has not disappeared, but today it is of a different origin.

The UK Government is committed to an 80% reduction in carbon emissions by 2050. 46% of present UK energy consumption is in existing buildings, with about 30% in domestic buildings and 16% in non-domestic buildings (Fig. 1).

There has been no significant reduction in domestic energy use since 1970, although energy consumption for industry has decreased by 60% over the same period. To meet the 2050 carbon obligations by reducing CO₂ emission to only 20% of current value (about 9 mteo), all new homes and about 87% of existing buildings (approx. 22m homes) that are estimated to be still here in 2050 need to be retrofitted. This can only be achieved by strict energy efficiency measures in addition to an increase in the application of renewable energy systems in UK dwellings.

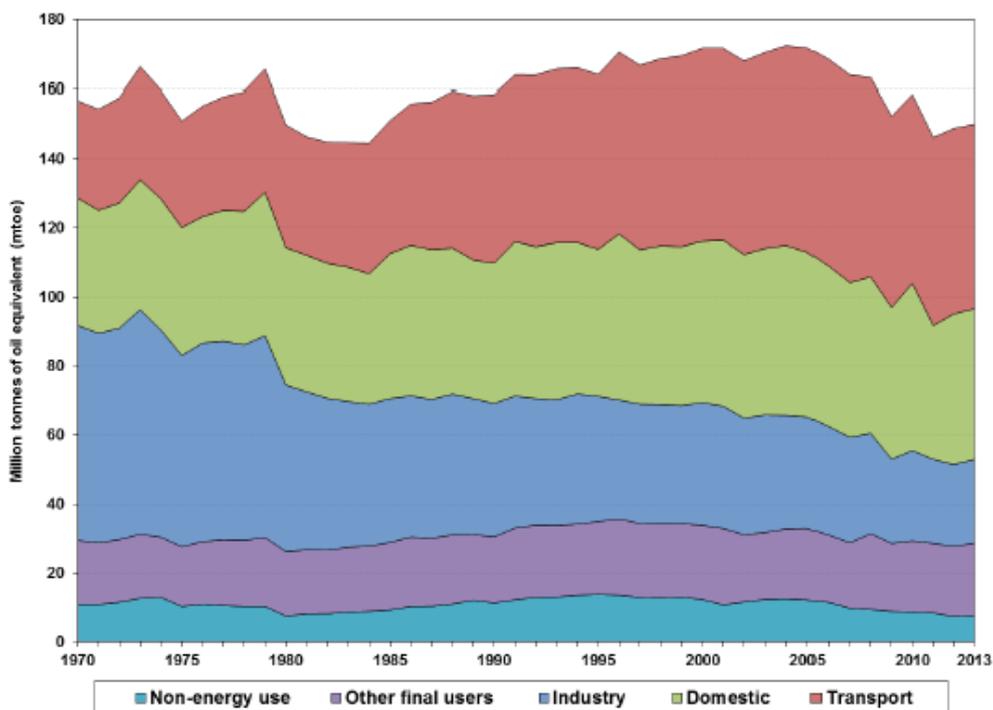


Figure 1. UK energy consumption by sector (1970 to 2013)-DECC (2014).

To meet future obligations, UK dwellings will need to be much more energy efficient than most existing homes and what the current building regulations stipulate. This will

involve improving fabric insulation, reducing fortuitous air leakage through the dwelling fabric, installing more energy efficient domestic systems as well as installing renewable energy systems to provide a large part of the energy consumption. However, these stringent measures need to be carefully implemented with appropriate measures taken to avoid major problems in future dwellings.

A number of case studies exist on retrofitting existing dwellings as well as monitoring low or zero energy dwellings. A sample of these studies is reported here with the focus mainly on ventilation and indoor air quality performances.

It will be shown that future dwellings (both new build and retrofitted) will be well insulated and very airtight in order to meet the country's carbon reduction strategy. In order to meet these criteria, continuous mechanical ventilation will undoubtedly be a necessary part of all dwellings. However, lessons gained from various case studies show that adequate measures need to be taken to ensure proper installation, operation and maintenance of these systems in future dwellings of the UK.

2. IMPACT OF AIR QUALITY ON HEALTH

The main sources of pollutants in dwellings are combustion of fuel, tobacco smoke, building fabric, furnishing and consumer products, office equipment, people, pets, and soil gas intrusion and outdoor air. The main pollutants are particulate matter (PM₁₀, PM_{2.5}, ultrafine particles and fibres), carbon monoxide (CO), excess moisture, nitrogen oxides (NO₂), sulphur dioxide (SO₂), volatile organic compounds (very volatile, volatile and semi-volatile), formaldehyde, radon, ozone, ammonia and biological particulates (allergens, bacteria, fungi), see Fig. 2.

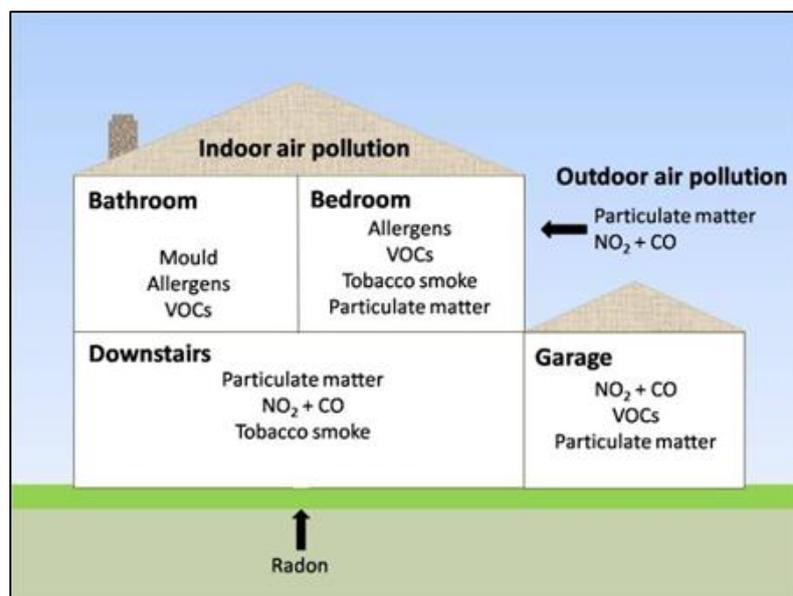


Figure 2. Typical distribution of the main air pollutants in a house.

WHO's (2005) recommended concentration limits for some of the commonly found pollutants and particulates are given in Table 1.

Table 1. WHO air quality guidelines (2005)

Pollutant	Annual Mean Concentration ($\mu\text{g}/\text{m}^3$)	24-Hour Mean Concentration ($\mu\text{g}/\text{m}^3$)	8-Hour Concentration ($\mu\text{g}/\text{m}^3$)	1-Hour Concentration ($\mu\text{g}/\text{m}^3$)
PM ₁₀	20	50		
PM _{2.5}	10	25		
NO ₂	40			200
SO ₂		24		
O ₃			100	
TVOC		300		

2.1 Air quality Studies in Dwellings

2.1.1 Venn *et al.* (2003) investigated the relationship between exposure to some indoor air pollutants and the occurrence of childhood wheezing illness in a study of 410 homes in Nottingham. They reported indoor concentrations of total volatile organic compounds (TVOCs), some individual VOCs, formaldehyde, and NO₂ and took measurements of surface dampness and recorded presence of mould. Visible mould was only identified in 11 homes but was significantly associated with an increased risk of wheezing illness. The risk of wheezing was significantly increased by dampness. Among the 193 cases of children with persistent wheezing, formaldehyde and damp were associated with more frequent nocturnal symptoms.

2.1.2 A large scale study of indoor pollutants in UK homes was carried out between 1997 and 1999 and this measured concentrations of CO, nitrogen dioxide, formaldehyde and total volatile organic compounds (TVOCs) in 876 homes selected as representative of homes in England (Coward *et al.*, 2001; Coward *et al.*, 2002; Brown *et al.*, 2002). As part of this study relationships between pollutant levels and household activities were explored and among the statistically significant findings were that concentrations of formaldehyde and VOCs were highest in newer homes. The results of TVOC measurements showed that pre-1919 homes had significantly lower TVOC levels than homes built since 1990 (means of 147 vs. 269 $\mu\text{g}/\text{m}^3$). The change in TVOC became more marked with homes built during late 1990's, see Fig. 3. It is not known whether these concentrations were higher because of stronger sources of these compounds in newer homes or whether lower ventilation rates occurred resulting in less efficient removal of the compounds in the indoor air, or a combination of both of these factors.

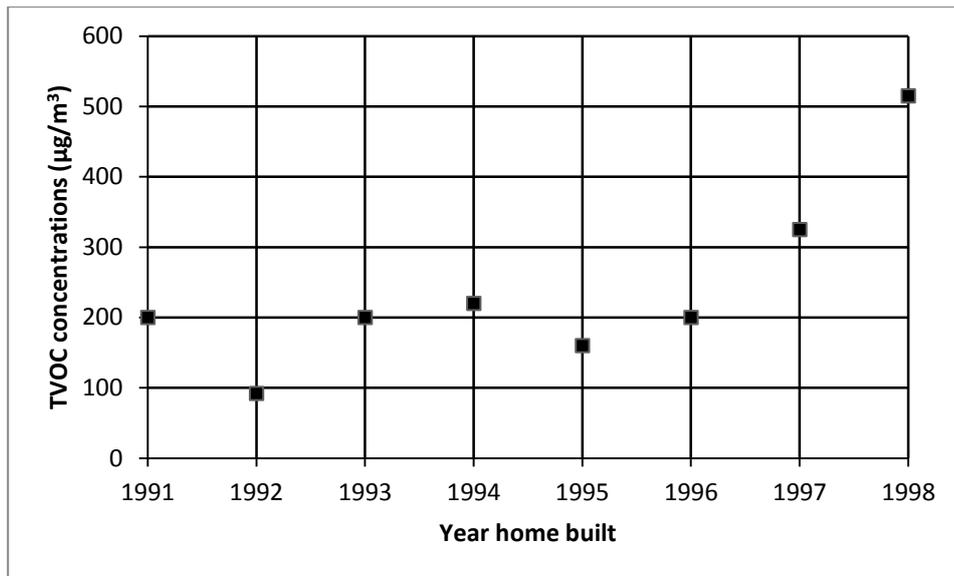


Figure 3. TVOC levels in English homes built since 1990 (Brown, *et al.*, 2002)

2.1.3 The European Commission Scientific Committee on Health and Environmental Risks reviewed current approaches to risk assessment of indoor air pollutants (SCHER, 2007). It concluded that indoor air may contain over 900 chemicals, particles and biological materials with potential health effects. They note that concentrations of pollutants are usually higher indoors than outdoors and that people spend most of their time indoors.

Most indoor air pollutants consist of chemicals released, for example, by the use of cleaning products, air fresheners, pesticides and emissions from furniture and construction materials, heating and cooking. In addition, outdoor sources may contribute to indoor air pollution. Aspects such as thermal insulation, ventilation rates and microbiological contaminants may also play a role in inducing a range of health conditions including; asthma and other respiratory disorders, allergies, cardio-vascular disease and cancer.

2.2 Studies on Air Pollution and Health

2.2.1 Fisk *et al.* (2007) undertook a meta-analysis of 33 studies investigating an association between occurrence of indoor dampness and mould with adverse health effects. This found building dampness and mould to be associated with an approximate 30 to 50% increase in a variety of respiratory and asthma-related health outcomes. The studies included those recording visible dampness and or mould, or mould odour, by investigators or the occupants themselves.

2.2.2 A recent study by Exeter University, on 944 social houses in Cornwall, studied the link between energy efficiency of dwellings (evaluated in terms of the Standard Assessment Procedure – SAP rating) and the prevalence of asthma. The study found that a unit increase in SAP rating was associated with a 2% increased risk of asthma symptoms, Sharpe *et al.* (2015). It also found that the presence of mould was linked to a

two-fold increase in asthma. The greatest risk was found to be for dwellings with SAP > 71, Fig. 4.

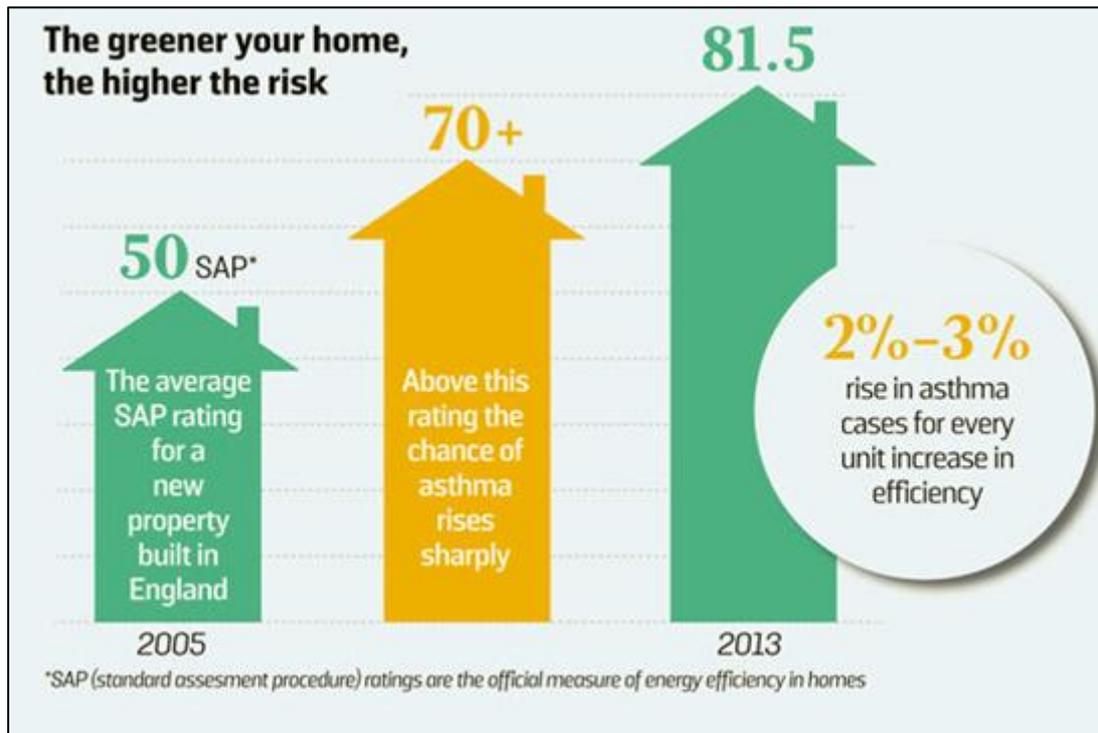


Figure 4. Impact of UK housing energy efficiency on asthma symptom

2.2.3 A BRE study of 10 Code Level 6 homes at GreenWatt Way, Chelvely, Slough (BRE Report, 2011), produced a range of Mean TVOC concentrations between 247 and 3900 $\mu\text{g}/\text{m}^3$ when measurements were taken on completion of these dwellings and a range of 120 to 420 $\mu\text{g}/\text{m}^3$ nine months after occupancy. Although the World Health Organisation (WHO) recommended limit of 300 $\mu\text{g}/\text{m}^3$ was exceeded in some dwellings, the levels 9 months after building work completion were considerably lower than those measured shortly after completion. In addition to TVOCs, formaldehyde concentrations were measured in different rooms during occupancy giving a range from 29 to 92 $\mu\text{g}/\text{m}^3$. In comparison, WHO's recommended 30-minute exposure to formaldehyde is 100 $\mu\text{g}/\text{m}^3$. The levels of relative humidity indoors were in the range 40 to 51% which were within the normal range expected for the time of year. The air change rates measured in these dwellings using tracer gas technique was found to be in the ranges of 0.56 to 0.82 ac/h with one exception of 3.1 ac/h in one of the dwellings. Although these air change rates are within the acceptable range (i.e. > 0.5 ac/h) it is seen that pollution concentrations are in most cases above the recommended limits. It is clear from this study on 10 zero carbon dwellings that the indoor air pollution could be considerably above the recommended limits in less well ventilated low energy dwellings.

2.2.4 Craig *et al.* (2008) working with a network of experts called NERAM (Network for Environmental Risk Assessment and Management) evaluated the impact of air pollution due to particulate matter (PM) on mortality and published the findings following five annual meetings as well as the results of supporting international

research. Figure 6 shows some results from the literature of the relative risk estimates for the association between long term exposure to PM and mortality.

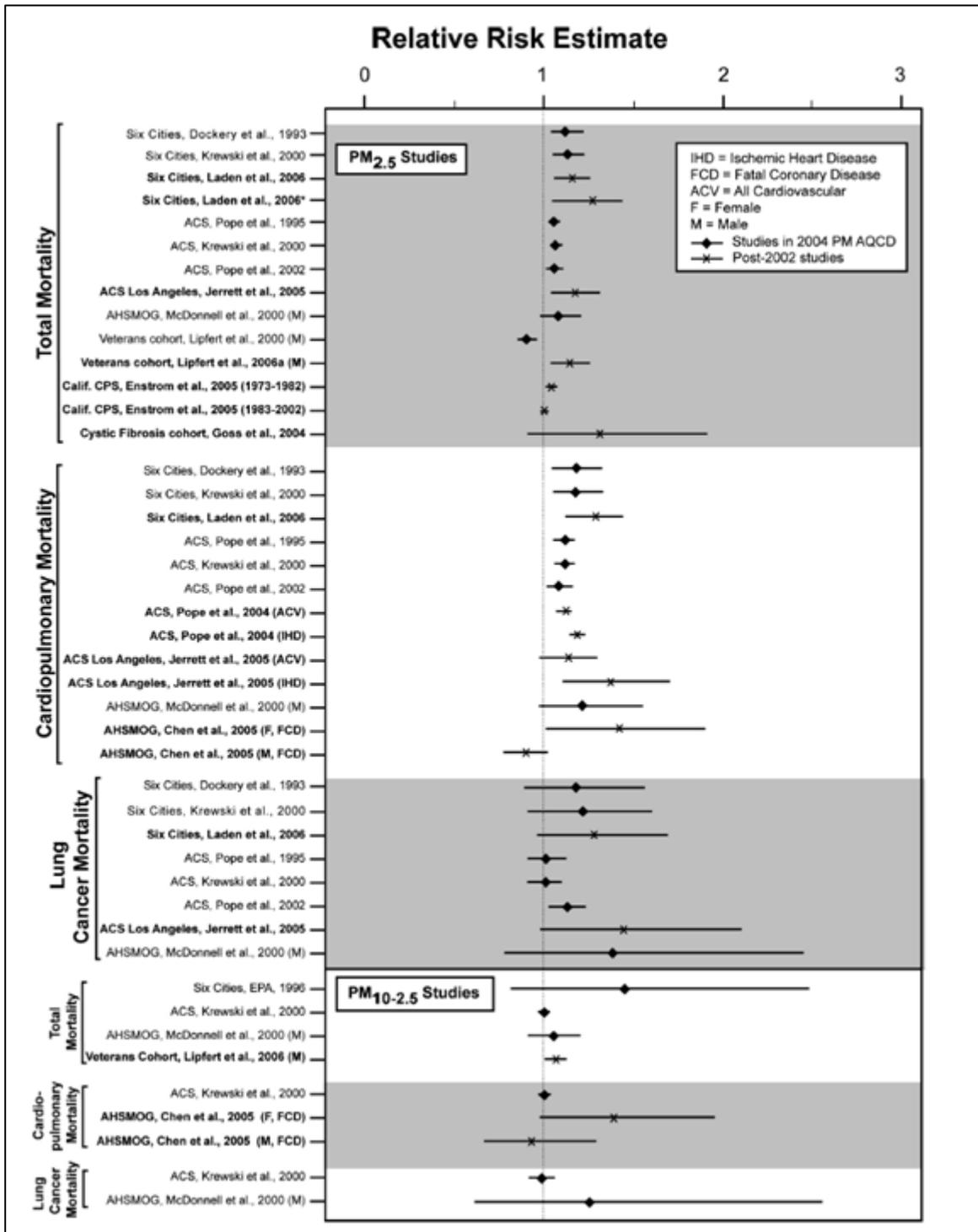


Figure 5. Relative risk estimates (and 95% confidence intervals) for associations between long-term exposure to PM (per 10 PM_{10-2.5}) and mortality (Craig *et al.* 2008).

2.2.5 WHO (2006) analysed the results from two main studies (European APHEA2, Spix *et al.*, 1998, and the United States' National Morbidity, Mortality, and Air Pollution Study - NMMAPS projects, WHO, 2006) relating the effect of air pollution concentrations on mortality. The results shown in the Fig. 6 show elevated PM exposure for a few days is associated with a small increased risk of mortality. The NMMAPS estimate is based on the largest 90 US cities.

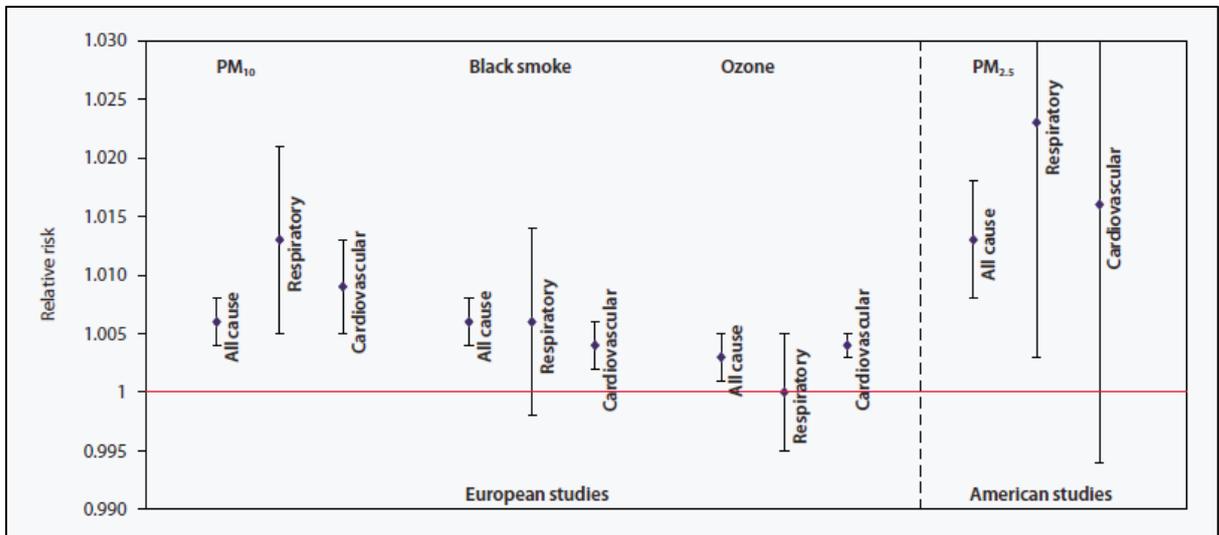


Figure 6. Pooled estimates of relative risks of mortality for a 10 µg/m³ increase in pollutant from Meta-analysis of European time series studies (WHO, 2006).

2.2.6 The House of Commons Environmental Audit Committee has been publishing reports on air quality issues since 2010 (Environmental Audit Committee, 2014). These studies are mainly focused on traffic pollution which has a direct impact on air quality in dwellings particularly in urban areas. Unfortunately, the Committee's recommendations in previous reports have not been implemented by Government, even though air pollution continues to be a major problem costing 29,000 UK citizens lives per year.

2.2.7 A World Health Organisation (WHO) expert meeting has recommended that international guidance should be developed on "healthy housing" to help prevent a wide range of diseases (WHO, 2010). Key housing related health risks identified in the recommendations were respiratory and cardiovascular diseases from indoor air pollution.

Inadequate ventilation is also associated with a higher risk of airborne infectious disease transmission, including tuberculosis, as well as the accumulation of indoor pollutants and dampness, which are factors in the development of allergies and asthma. Poor housing quality and design can also exacerbate the health impacts from exposure to temperature extremes, which are occurring more frequently due to climate change. It is therefore significant that home occupants need to know how to use their homes in a healthier manner, particularly when homes are made more weather and airtight to save energy.

There is clear evidence from the above studies, and many others not reported here, that as the level of air pollution (both indoors and outdoors) increases above the recommended limits, people's health is directly affected. This impact is not only noticed on elevation of health symptoms but also on the increase in hospital visits and mortality rates.

3. IMPACT OF ENERGY EFFICIENCY ON INDOOR AIR QUALITY

One of a range of UK government actions to mitigate the effects of climate change is to reduce carbon emissions from the built environment to the atmosphere. This has resulted in an on-going process of change in the way we construct and heat new buildings as well as renovate existing buildings to improve their energy efficiency. Broadly these changes result in more airtight and highly insulated structures. These changes can impact the quality of the indoor environment and there are concerns that some of these changes could have adverse consequences for occupants' health.

There are about 24 million homes in the United Kingdom. Unlike many countries, the vast majority of dwellings in the UK are houses - 86% in England. The stock is also fairly old. In England, 39% predate 1944, 42% were built between 1945 and 1980 (when thermal standards were raised significantly), and 19% after 1980. It is estimated that around a third of dwellings which will comprise the 2050 stock have yet to be built, and that by the same date 75% of the current stock will still exist, DCLG (2007).

The average Standard Assessment Procedure (SAP) rating for dwellings in England has improved from 42 in 1996 to 48 in 2005 and new homes score 80+ (DCLG, 2007) but it is estimated that about 22m existing homes will need to be retrofitted by 2050 in order to meet the carbon emission obligations.

A number of studies have been carried out under different types of energy saving schemes, e.g. Green Deal, Energy Company Obligation (ECO), etc. by retrofitting existing dwellings as well as monitoring low or zero carbon dwellings. The main findings of these studies are summarised below.

3.1 Affinity Sutton Study

Affinity Sutton Ltd, which is a major housing association, carried out a number of retrofitting programmes (FutureFit) to some of their dwellings across England to investigate the performance of those dwellings and the impact upon residents after carrying out energy saving measures (Affinity Sutton, 2013). Twenty-two common types of housing were identified across Affinity Sutton's stock, representing around 75% of England's total housing stock. A total of 102 homes were retrofitted around the country using one of three packages of work, led by budgetary targets, not CO₂, and following the energy hierarchy: low (£6,500), medium (£10,000) and high (£25,000). Half of the 102 homes, and an additional group of 50 homes, then took part in FutureFit Living, a programme of energy lifestyle advice delivered throughout the monitoring period, but with a focus on heating.

The study concluded that condensation in the dwellings can increase after retrofit works, even when appropriate ventilation is installed, which was attributed to lifestyle. They recommend that knock-on effects of improving air tightness must be considered in any lifestyle advice/resident engagement to prevent these issues. Figure 7 shows the level of residents' complaints following retrofitting where ventilation complaints were 27% and mould growth was 17% (Affinity Sutton, 2013).

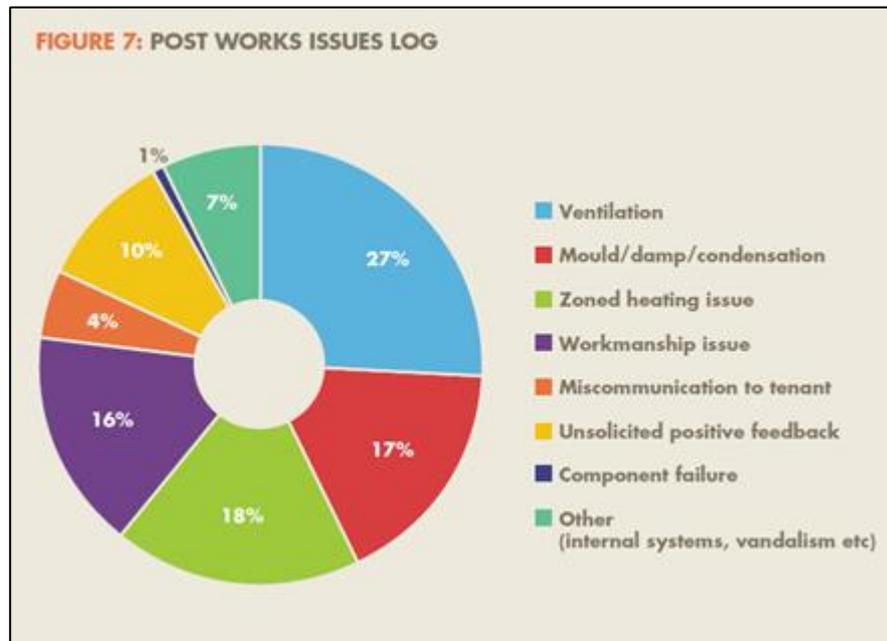


Figure 7. Rates of residents' complaints following retrofitting (Affinity Sutton, 2013).

3.3 NHBC Study

The National House Building Council (NHBC) commissioned air leakage testing on newly constructed homes between 2007 and 2009 (around 5500 tests). The tests revealed air permeability results better than $10 \text{ m}^3/(\text{h m}^2)$ being achieved on a regular basis and that there was an improving trend - Figure 8 (NHBC, 2011). This shows that a large majority of homes tested were not able to provide the 0.5 ac/h which is the recommended minimum rate..

In response to the suggestions that new homes might become leakier as they age, due to shrinkage and settlement, and that this would provide additional ventilation, the NHBC sampled 23 of the dwellings with initial air leakage less than $10 \text{ m}^3/(\text{h m}^2)$ to air leakage re-testing one to three years later to establish how their air permeability had changed. Following re-testing carried out in 2010 to allow for settling of dwellings, results showed that 83% of the dwellings achieved an air-tightness of $5 \text{ m}^3/(\text{h m}^2)$ which is expected to provide only about 0.25 ac/h, see Fig. 9. This research found that, whilst two-thirds of homes did become leakier, the remaining third actually became more airtight. It appears that the type of dwelling, construction, heating and ventilation all have a bearing on the extent to which air permeability changes.

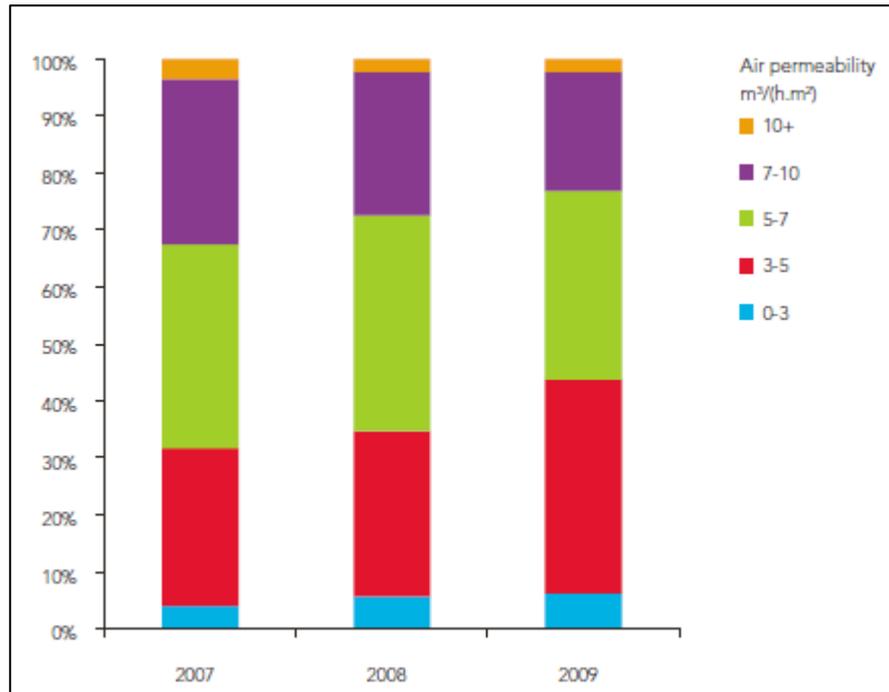


Figure 8. NHBC pressure test results for new homes (NHBC, 2011).

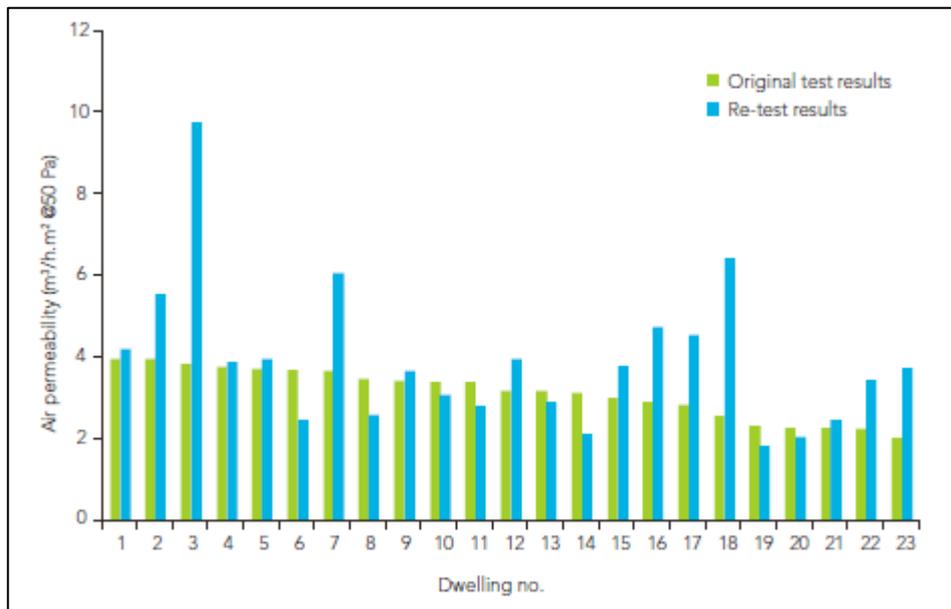


Figure 9. Air leakage retest results for 23 homes tighter than 10 m³/(h m²)-NHBC (2011)

As a result of these studies, NHBC (NHBC, 2009) warned that a lack of adequate ventilation in these homes could result in a build-up of pollutants released by furnishings and building insulation materials, alongside humidity and condensation. The possible health effects of poor indoor air quality could include asthma, severe respiratory conditions or even cancer, the report warned. The report states that social tenants are particularly at risk of poor indoor air quality as they normally live in fully

occupied dwellings with less air movement and also because they are more likely to spend more time at home and also try to reduce heating and ventilation costs.

As UK developers are keen to boost their green credentials, they are routinely building dwellings more airtight than $10 \text{ m}^3/(\text{h m}^2)$. The concurrent notional dwelling specified air-tightness in the Building Regulations Part L1A (2103) is $5 \text{ m}^3/(\text{h m}^2)$. NHBC (NHBC, 2009) recommends the use of mechanical ventilation for dwellings with air-tightness below $10 \text{ m}^3/(\text{h m}^2)$ while BRE recommends a minimum house air change rate of 0.5 ac/h in order to avoid moisture build-up. Typically for a dwelling, an air leakage of $10 \text{ m}^3/(\text{h m}^2)$ at 50 Pa corresponds to an air change rate of about 0.5 ac/h under normal conditions.

3.4 BRE Study

A BRE study of 37 homes in England, built since 1995 and undertaken in 2002 did involve simultaneous measurements of air quality and rates of ventilation (Dimitroulopoulou, *et al.*, 2005). All homes in the study had central heating with radiators and were double glazed with trickle ventilators in the window units to provide background ventilation. Measurements of airtightness of the homes with windows and doors closed, expressed as ac/h at 50 Pa, were undertaken using a fan pressurisation technique prior to the monitoring of indoor pollutants. VOCs, NO_2 , CO and formaldehyde were measured using diffusive samplers with an exposure period of 3 days to 2 weeks, depending on the pollutant. PM_{10} was measured using a pumped gravimetric method with a sampling period of 24 hours. Information was collected about the characteristics of the properties and the activities of occupants using questionnaires. Concurrent with the pollution measurements, a perfluorocarbon tracer (PFT) method was used to determine the mean rate of air exchange of the indoor air with outside air for the 2 week period.

In winter, 68% of homes had a whole house ventilation rate below 0.5 ac/h, which is necessary to avoid condensation according to BRE research. In summer, 30% of homes had a whole house ventilation rate below 0.5 ach. The mean air leakage rate of the 37 houses at 50 Pa (determined by pressurisation of the houses using a fan) was 12.9 ac/h in winter and 13.9 ach in summer (a sample of 13 houses). The 37 houses built after 1995 were not more airtight than other housing stock (13.1 ac/h at 50 Pa in a sample of 471 dwellings). It was noticed that 70% of homes had air leakage rates $> 10 \text{ ac/h}$ at 50 Pa.

The results from the measurements were statistically analysed, based on data from questionnaires, including house characteristics and occupant activity diaries. The relationships between the ventilation rate for the dwellings and the concentration of some main indoor pollutants were found as well as correlations between certain sources and pollution concentrations, such as the presence of a gas cooker and the concentration of NO_2 . Among the statistically significant findings were that concentrations of formaldehyde and VOCs were highest in newer homes. It was not established whether these concentrations were higher because of stronger sources of these compounds in newer homes or whether lower ventilation rates occurred,

resulting in less efficient removal of the compounds in the indoor air, or a combination of both of these factors.

The above studies provide substantial evidence on the link between low ventilation rates in dwellings and the degradation of indoor air quality as a result of insufficient air change rate in dwellings. The impact of low ventilation on IAQ is expected to become even more acute than the above studies have shown as air-tightness of new and retrofitted low energy buildings become a legal requirement at some point in the next few years. Therefore, it is paramount that adequate provisions are put in place to deal with future dwellings in order to alleviate serious health impacts on the occupants.

4. IMPACT OF FUTURE DWELLINGS ON HEALTH

The study by Exeter University reported earlier (Sharpe *et al.*, 2015) predicted an increase in asthma symptoms of at least 2% corresponding to each SAP increase for dwellings with SAP rating above band D. Based on this study, figure 10 shows the projected increase in asthma symptoms for airtight dwellings, with no mechanical ventilation installed, above SAP band D rating. The SAP bands shown in this figure are as follows:

- Band D = 55 to 68
- Band C = 69 to 80
- Band B = 81 to 91
- Band A = 92 or more

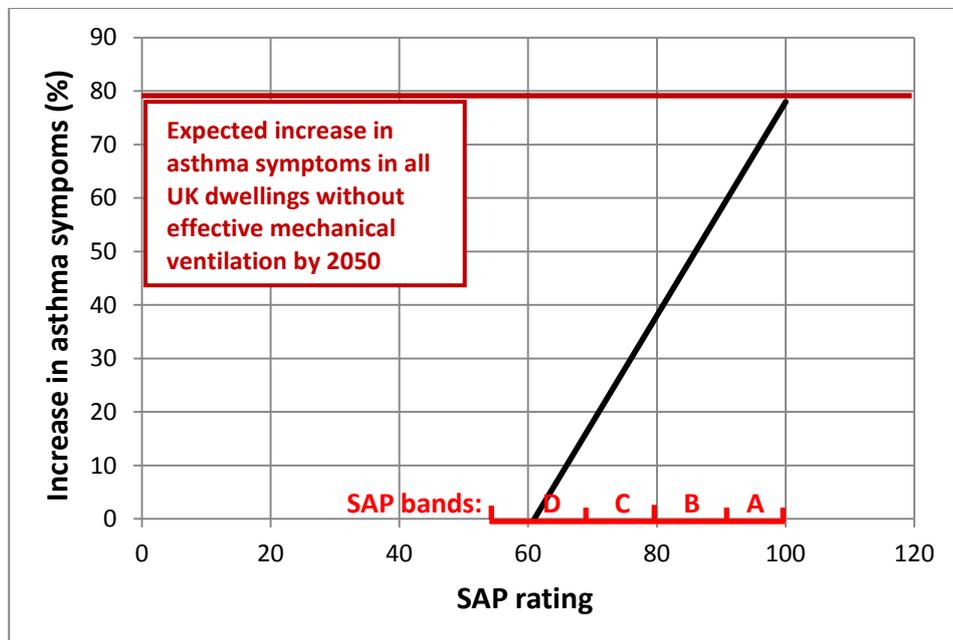


Figure 10. Projected increase in asthma symptoms with SAP rating by 2050

The figure shows that within the next few years when we expect zero, or near-zero, energy dwellings to become mandatory and current dwellings are refurbished to meet the UK Government carbon reduction commitments, there will be an increase in

asthma sufferers of the order of 80% from current level unless constructive action is taken to improve the indoor air quality in future UK dwellings.

The health impact of energy efficiency of dwellings reported above does not specifically consider the impact of SAP on indoor air quality, although it was clear from that study that there is deterioration in IAQ as dwellings become more energy efficient. However, the BRE study reported earlier (Dimitroulopoulou, *et al.*, 2005 and Brown, *et al.*, 2002) did involve measurement of indoor pollutants in a sample of 37 homes in England built since 1995. Using this data it is possible to project levels of common pollutants in future homes with the absence of mechanical ventilation. Figures 11(a), (b) and (c) show projected levels for TVOC, NO₂ and PM₁₀ respectively, covering current and expected air-tightness levels for future UK dwellings without effective mechanical ventilation.

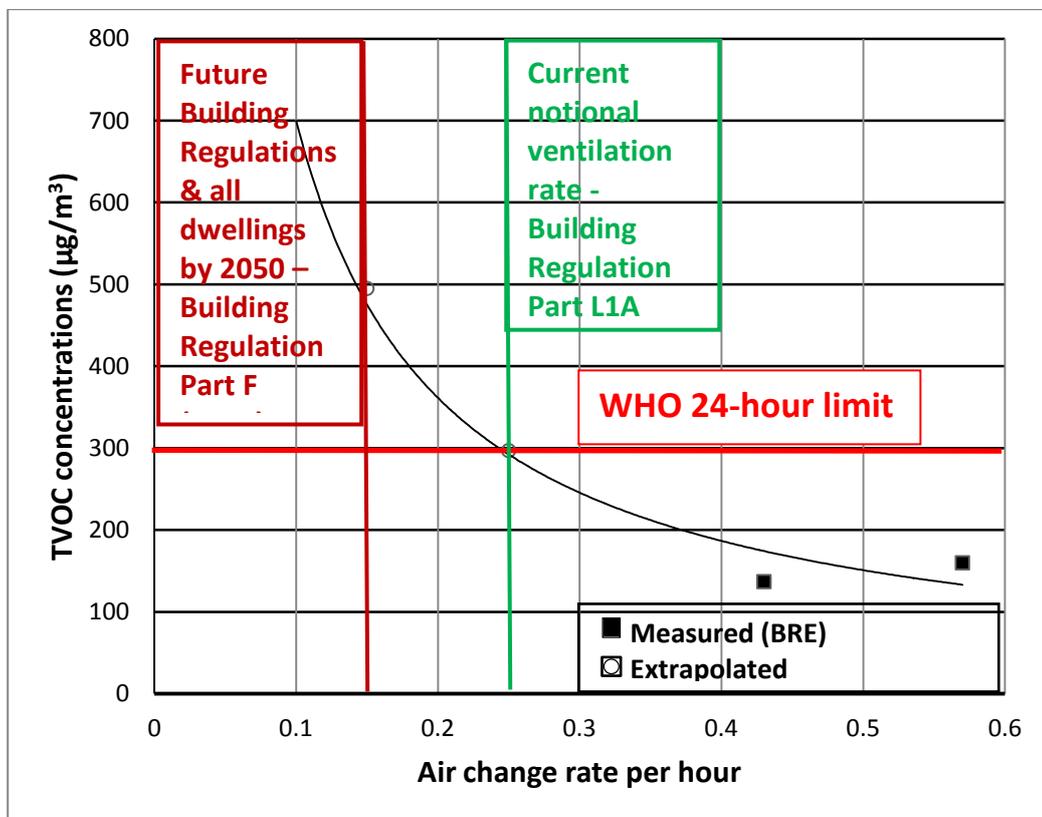


Figure 11 (a). Effect of air change rate on predicted TVOC levels in future dwellings

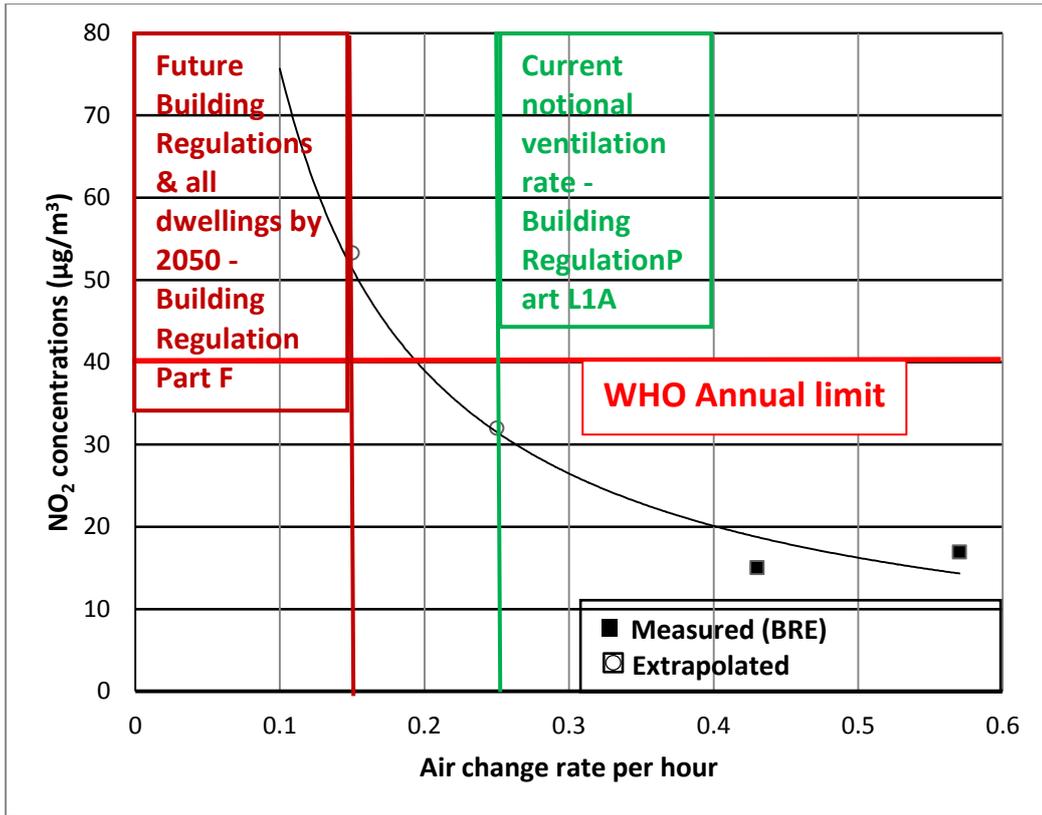


Figure 11(b). Effect of air change rate on predicted NO₂ levels in future dwellings

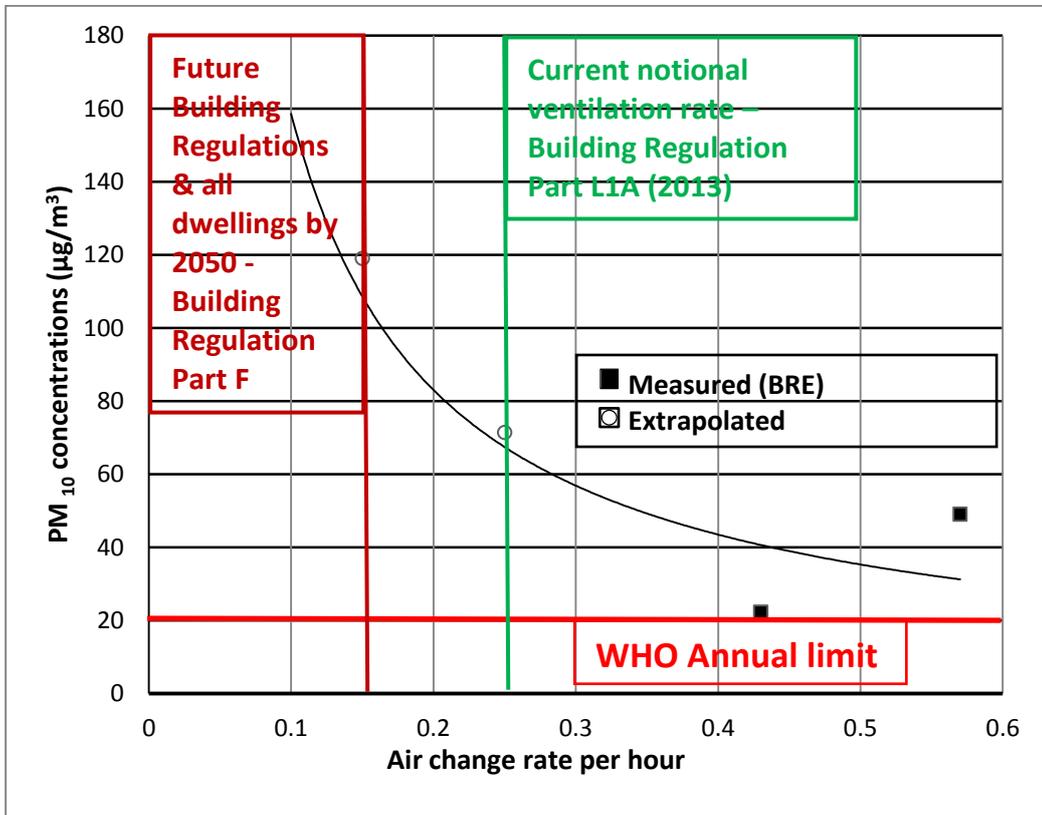


Figure 11(c). Effect of air change rate on predicted PM₁₀ levels in future dwellings

As shown in Fig. 11(a), TVOC levels are expected to be on the border-line of WHO recommendations for dwellings built or renovated to concurrent notional dwelling specification (Building Regulation, 2013a) air-tightness limits of 0.25 ac/h (equivalent to an air-tightness of $5 \text{ m}^3/(\text{h m}^2)$) - as indicated by the green lines on the graphs. However, with tighter construction of future dwellings and retrofitting of existing dwellings, which are expected to have an air change rate of around 0.15 ac/h (equivalent to an air-tightness of $3 \text{ m}^3/(\text{h m}^2)$, Building Regulations, 2010), TVOC levels are expected to exceed the WHO limits in all future dwellings without effective mechanical ventilation – as indicated by the brown lines.

Similar predictions can be made for indoor NO_2 concentrations, see Fig. 11(b). However, Fig. 11(c) shows that even with current air leakage rate recommendation of $5 \text{ m}^3/(\text{h m}^2)$, (equivalent to natural ventilation rate of 0.25 ac/h), PM_{10} concentrations exceed the WHO recommended levels and are expected to be substantially higher in future dwellings without effective mechanical ventilation.

Figures 10 and 11 show the expected limits for predicted asthma increases and indoor pollutant levels if future dwellings (new and old) are not equipped with effective mechanical ventilation systems. They also clearly demonstrate a health requirement for mechanical ventilation systems that are capable of providing a continuous air change rate of at least 0.5 ac/h. Failing that, one would expect major negative health impacts on the occupants of all dwellings in the UK by 2050.

5. RECOMMENDATIONS FOR VENTILATING FUTURE DWELLINGS

The National House Building Council (NHBC, 2011) study concluded that in order to satisfy future energy use demands in homes it is expected that mechanical ventilation with heat recovery will need to be applied in order to achieve an acceptable indoor climate. However, there is a possibility that householders would seek to counteract poor air quality or lack of the feel of ‘freshness’ by opening windows on a regular basis, thereby serving to offset the inherent benefits of a structure built to standards of high energy efficiency fitted with a continuously operating ventilation system.

Lack of long-term maintenance of ventilation equipment is one of the biggest risks to indoor air quality for mechanically ventilated dwellings. At this time, it seems clear that for any improvement to the air quality in airtight homes, house builders must address the complex interaction between design, system operation and human behaviour.

Approved Document F, Ventilation (Building Regulations, 2010), recommends increasing the ventilation provision for dwellings with high design airtightness ($\leq 5 \text{ m}^3/(\text{h m}^2)$ at 50 Pa – equivalent to $\leq 0.25 \text{ ac/h}$) and makes reference to a new guide on installing, inspecting, testing and commissioning ventilation systems in dwellings (DCLG, 2011). Building Regulation Part L1A provides a limit value for the required measured air

permeability of $10 \text{ m}^3/(\text{h m}^2)$ at 50 Pa (Building Regulation, 2013a) but recommends a notional air leakage of only $5 \text{ m}^3/(\text{h m}^2)$ for the whole dwelling.

The main changes to the legal requirements in Approved Document F since the 2006 edition are (Building Regulation, 2013a, 2013b):

- Maintenance requirements so that the Mechanical Ventilation (MV) system can be operated to provide adequate flow. All fixed MV systems are to be commissioned and a notice provided to the Building Control Body;
- For MV systems installed in new dwellings air flow rates shall be measured on site and notice given to the Building Control Body;
- The owner shall be given sufficient information about the ventilation system and its maintenance requirements so that the system can be operated to provide adequate flow.

Since MVHR systems are more energy efficient than other types (e.g. mechanical exhaust system, mechanical supply system and mechanical supply and exhaust system) it is to be recommended that MVHR systems be installed in new developments and major retrofitting for raising the energy performance of dwellings. However, almost all of the evidence that is available on MVHR systems (see Appendix A) points to a range of issues which need to be addressed to make sure these systems perform as they should in practice. Some of the issues that need special attention in installing, maintaining and operating MVHR systems are:

- MVHR systems should be installed by trained and experienced ventilation system installers to ensure proper distribution of air (both extract and supply air locations) around the dwelling. The installation should comply with the design and must ensure that systems are installed with the MVHR fan unit appropriately located and mounted and the ductwork correctly routed and connected. In addition, adequate thermal and sound insulation of the MVHR unit and all ductwork must be carried out to avoid freezing problems of the heat exchanger coils in winter and high noise levels during operation.
- Evidence suggests that commissioning is a particularly common area of weakness, although clearly it is essential for the correct functioning of MVHR systems. Commissioning must be undertaken by a competent individual and the recommendations of the Domestic Ventilation Compliance Guide (DGLC, 2011) should be followed.
- All MVHR systems should be fitted with visual displays that clearly show that the system is working, whether it is in normal or boost and/or bypass mode and when maintenance is needed. A user-centred approach to controls should be adopted, with appropriate simple user controls and indicators provided. Also, advanced sensing controls (demand control ventilation) based on movement and/or humidity/ CO_2 sensors would appear to offer the potential for maximising energy efficiency while ensuring that good IAQ is maintained.

6. CONCLUSIONS

Based on the information available from the medical, air quality and ventilation research and the development in Building Regulations for meeting the UK carbon reduction commitments, one can conclude that future dwellings (both new build and retrofitted) will be much more energy efficient than the current standard and will be very airtight.

To meet acceptable indoor air quality and humidity levels, it was projected from current knowledge that it is necessary to maintain an average air change rate of at least 0.5 ac/h, which is twice the level of currently recommended notional air infiltration rates for dwellings (Part L1A, 2013). However, such rates of ventilation will not be achievable by natural ventilation in modern or retrofitted homes.

Evidence indicates that UK dwellings will need to rely on mechanical ventilation to provide the required rates of air exchange for occupants. Although in principle this could be achievable by using extract ventilation, with passive air inlets or a balanced mechanical system, neither of these approaches will meet the strict energy performance criteria of future dwellings.

It can therefore be concluded that the type of mechanical system to use for new homes and indeed for properly retrofitted dwellings should be MVHR (Mechanical Ventilation with Heat Recovery) as, in principle, this is far more energy efficient than other systems.

However, there are known short-comings in the design, installation, operation and maintenance of MVHR systems partly due to inadequate design and installation, and partly due to a lack of operational knowledge by home owners. These short-comings need to be addressed by legislators, house builders and homeowners to ensure maximum efficiency and improvement in IAQ and a reduction in adverse health effects relating to IAQ.

APPENDIX A

RECENT EXPERIENCE WITH MVHR

A Mechanical Ventilation with Heat Recovery (MVHR) system is multi-room ducted system that combines supply and extract ventilation for a dwelling. It is designed to continuously provide fresh air to different rooms whilst pre-heating the supply air, by recovering heat from the exhaust air, before distributing it to the rooms. Warm, moist air is extracted from wet rooms, such as bathrooms and kitchens, and is used to warm the supply air from outside. The warmed air is then distributed throughout the dwelling via supply grilles, typically placed on ceilings. A well-designed and maintained MVHR system could achieve up to 90% heat recovery from the exhaust air which is then passed to the incoming air. A typical system for a house is shown in Fig. 12.

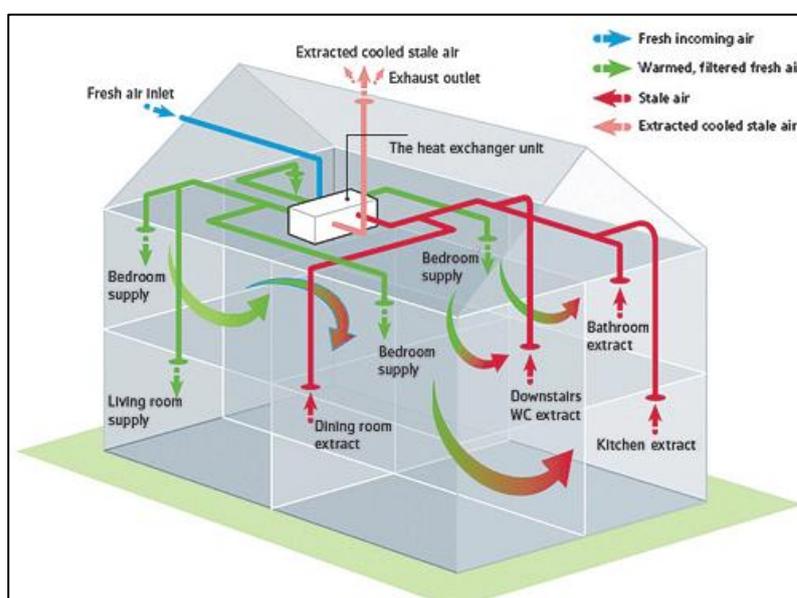


Figure 12. Mechanical ventilation with heat recovery system (MVHR)

An NHBC report (NHBC, 2013a) which was based on test results from a number of studies on energy efficient, airtight dwellings fitted with MVHR systems during 2012 concluded that a variety of airborne pollutants are present in homes and some are associated with serious health effects, including asthma, lung cancer, chronic obstructive pulmonary disease and cardiovascular disease. As new homes become more airtight, adequate ventilation is relied upon increasingly to maintain satisfactory IAQ. The report concludes that it is essential to have ventilation systems of all types to successfully deliver adequate indoor air quality, but as the number of MVHR systems being installed continues to grow and due to its relative complexity, there is a need for particular attention to this type of system. With regards to the performance of the MVHR systems it was concluded that many of the systems initially installed did not meet expectations and their performance was in many cases inadequate partly due to installing the wrong types and/or poor installation/commissioning, maintenance or misuse. This led to replacing many of those systems (NHBC, 2013a).

In addition to the NHBC report above, another 2013 report (NHBC, 2013b), included information gathered from different sources and highlighted the performance of low energy, airtight dwellings that have MVHR systems for providing the required ventilation to the dwellings. This study concerned ten homes built by the energy supplier Scottish and Southern Energy (SSE) in 2009 on an ex-industrial site in Chalvey, near Slough, Berkshire, see Fig. 13. Achieving Code for Sustainable Homes Level 6, the homes were conceived as a way of improving SSE's understanding of domestic energy generation and use in homes of the future.



Figure 13. The GreenWatt Way zero carbon development in Chalvey, Slough

In one corner of the site is the 'Energy Centre' which provides for the space and hot water heating requirements of the homes (by means of a biomass boiler, ground and air source heat pumps and solar thermal panels). In addition electricity is generated from solar photovoltaic tiles fixed to the roofs of the homes. Six of the homes (four houses and two flats) are of masonry construction and the other four are timber frame houses. Ventilation to each of the homes is provided by means of an MVHR system, with fan units located within the roof spaces.

The homes were completed in September 2010 and occupied immediately by employees of SSE and Slough Borough Council nominees, all of whom agreed to participate in the research. Homes were monitored for a period of almost two years post-occupation, which spanned two heating seasons during which external temperatures fell to well below zero for extended periods.

The ventilation aspects of the GreenWatt Way development formed the basis of an NHBC Foundation and Zero Carbon Hub study, undertaken by BRE. The homes achieved a good standard of air-tightness, with results of between 2.6 and 5.7 m³/h/m² at 50 Pa measured at completion (NHBC, 2013b). Nine months after occupancy repeated

airtightness tests produced air leakage in the range of 2.8 to 6.5 m³/(h m²) (BRE Report , 2011).

The main findings from the extensive studies of all aspects of the MVHR systems at GreenWatt Way, along with recommendations for better practice where appropriate, may be summarised below under different categories.

Energy use in operation

The MVHR systems seemed to have used more energy than envisaged due to several factors, including inadequate wiring for permanent boost, effect of dirty filters (internal and external), and in some cases lack of fan power requiring the fans to be run at near boost speed to achieve the required air flow rates.

Insect filters

External filters were found to be clogged in some occasions mainly due to marked increases in power drawn by certain MVHR units at certain periods.

Noise

Occupants have remarked on noise issues associated with the MVHR systems, particularly when upstairs in the houses and at certain times of day. However, this was considered to be partly due to the extremely airtight and 'acoustically efficient' nature of the dwellings in which occupants do not pick up noise from external sources.

Level of occupant control

Part of the design intent for the homes is for minimisation of complexity when it comes to occupant control. However this has caused some issues for occupants, especially in terms of using and understanding the MVHR systems in their dwellings.

REFERENCES

Affinity Sutton (2013), FutureFit, Final Report – Part Two, **Affinity Sutton Group Ltd**, London.

BRE Report (2011), Assessment and Monitoring of Mechanical Ventilation Systems and Indoor Environments in Code Level 6 Homes, **Project Report 4**, August 2011.

Brown, *et al.* (2002), Indoor air quality in English homes – VOC, **Proceedings of Indoor Air 2002**, Paper 4C3p2, Monterey, California, USA.

Building Regulation (2010), Part F: Means of Ventilation, **Department for Communities and Local Government**, London.

Building Regulation (2013a), Part L1A: Conservation of fuel and power in dwellings, **Department for Communities and Local Government**, London.

Building Regulation (2013b), Amendments to the Approved Documents, **Department for Communities and Local Government**, London.

Coward S, Llewellyn J, Raw G, Brown V, Crump D and Ross D (2001), Indoor air quality in homes in England. **BRE report BR 433**, CRC Ltd, London, ISBN 1 86081 5308.

Coward S, Brown V M, Crump D R, Raw GJ and Llewellyn JW (2002), Indoor air quality in homes in England. Volatile Organic compounds. **BRE Report BR 446**, CRC Ltd., London, ISBN 1 86081 566 9.

DCLG (2007), English house condition survey 2005 annual report, **Department of Communities and Local Government**, London, June 2007.

DCLG (2011), Domestic Ventilation Compliance Guide: 2010 Edition, **Department of Communities and Local Government**, London.

DECC (2014), Energy Consumption in the UK- Chapter1: Overall consumption in the UK since 1970, **Department of Energy & Climate Change**, London.

Dimitroulopoulou S, D Crump, S K D Coward, V Brown, R Squire, H Mann, M White, B Pierce, D Ross (2005), Ventilation, air tightness and indoor air quality in new homes, **BRE report BR 477**, Building Research Establishment, Watford.

Environmental Audit Committee (2014), Action on air quality, Sixth Report, **Environmental Audit Committee**, House of Commons, UK.

Fisk W, Lei-Gomez, Mendell M (2007), Meta-analyses of the associations of respiratory health effects with dampness and mould in homes. **Indoor Air**, V17, N4, pp284–296).

NHBC (2009), Indoor air quality in high energy efficient homes - A review, **Report NF18**, NHBC.

NHBC (2011), Ageing and airtightness, **Report NF24**, NHBC.

NHBC (2013a), Mechanical ventilation with heat recovery in new homes, **Ventilation and Indoor Air Quality (VIAQ) Task Group**, Final Report, NHBC, July 2013.

NHBC (2013b), Assessment of MVHR systems and air quality in zero carbon homes **Report NF52**, NHBC.

Spix *et al.* (1998), Short-Term Effects of Air Pollution on Hospital Admissions of Respiratory Diseases in Europe: A Quantitative Summary of APHEA Study Results, **Archives of Environmental Health** V 53, No 1, February 1998.

SCHER (2007), *Opinion on risk assessment on indoor air quality*, **Scientific Committee on Health and Environmental Risks**, European Commission, May 2007

Sharpe, *et al.* (2015), Higher energy efficient homes are associated with increased risk of doctor-diagnosed asthma in a UK subpopulation, **Environment International**, V 75, pp 234-244.

Venn, *et al.* (2003), Effects of volatile organic damp and other environmental exposure in home on wheezing illness in children, **Thorax**, V 58-pp 955-960.

WHO (2005), Air quality guidelines on particulate matter, ozone, nitrogen dioxide and sulphur dioxide, **World Health Organization**, Geneva, Switzerland.

WHO (2006), Health risk of particulate matter from long-range trans-boundary air pollution, **World Health Organization**, Geneva, Switzerland.

WHO (2010), Meeting Report: Developing guidance for health protection in the built environment - mitigation and adaptation responses, **World Health Organization**, Geneva, Switzerland.

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