Good Homes Alliance



Ventilation and good indoor air quality in low energy homes

Finding proven good practice

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[1] Zero Carbon Hub report *Mechanical Ventilation with Heat Recovery in New Homes: Interim report 2012*
http://www.zerocarbonhub.org/resourcefiles/ViaqReport_web.pdf

Table of Contents

1 Introduction 11

1.1 Sustainable homes 11

1.2 Low energy homes 12

1.3 Indoor air quality and healthy homes 13

2 Ventilation and Indoor Air Quality 16

2.1 Regulation 17

2.2 Ventilation strategies 18

Passive stack ventilation (PSV) 18

Local extract fans 19

Mechanical supply ventilation 19

Whole house mechanical ventilation (with or without heat recovery) 20

Wind-Assisted Passive Heat Recovery System 20

2.3 What is good indoor air quality? 21

Carbon Dioxide 21

Relative Humidity 22

2.4 Measuring ventilation and indoor air quality 23

Problems with predicting indoor air quality 23

Measuring airtightness 23

Measuring indoor air quality 24

External Conditions 25

Perceived indoor air quality 25

Measuring Performance of Ventilation Systems 26

Analysis of measured indoor air quality data 26

3 Our Methodology 28

3.1 GHA Working Group 28

3.2 Search for Proven Good Indoor Air Quality 28

3.3 Selection criteria 29

3.4 Sources of Information 29

3.5 The data and information sought 29

3.6 How the data and information was analysed 30

3.7 Comparability of data 31
3.8 Additional Information 31
4 Examples 33
Presentation 34
Quantitative Analysis – a warning 34
Other Experience 34
4.1 Arun Crescent, Billingshurst, West Sussex 35
Monitoring details 35
Occupant feedback 35
Experience[2] 36
Lessons for future[2] 36
Future developments 36
References 36
4.2 BedZED, Wallington, Surrey 43
Monitoring details 43
Occupant feedback 44
Experience 44
Lessons for Future 44
Future developments 44
References 44
4.3 Dunoon, Tigh-Na-Cladach 47
Monitoring details 47
Occupant Feedback 48
Experience 48
Lessons for Future 48
References 48
4.4 Elm Tree Mews, New Earswick 51
Monitoring details 51
Occupant feedback 51
Experience 52
Lessons for future 52
References 52
4.5 Glasgow House 57

Monitoring 57
Experience 58
Lessons for Future 58
Future developments 58
References 58
4.6 Stamford Brook, Cheshire 61
Monitoring 61
Experience 62
Lessons for future 62
References 62
4.7 The Wintles, Bishop's Castle, Shropshire 67
Monitoring details 67
Occupant feedback 67
Experience 68
Lessons for Future 68
Future developments 68
References 68
4.8 Other Experience 72
Lincoln Close, Bladon, Oxfordshire 72
Elm Tree Mews House B 72
Dartmouth Avenue, Woking, and Manor Farm, Guildford 72
Grosvenor Waterside 73
5 Good Practice 74
5.1 Identifying good practice from the evidence 74
Feedback 74
Short-term problems 75
Chance 75
5.2 Achieving good indoor air quality 75
Design Stage 75
Construction 76
Installation and commissioning 77
Occupancy and Operation 77
Maintenance 78

6 Conclusions and recommendations 79
6.1 Finding examples of good practice 79
6.2 Good practice 79
6.3 Measurement methods 79
6.4 Feedback and learning 79
Short term: Fine tuning 80
Long term: Changes to process 80
6.5 The importance of feedback 81
7 Limitations of this report and further work 82
7.1 Limitations 82
7.2 Further work, future work 83
Beyond the scope of this investigation 83
Emerging evidence 83
Defining 'good' indoor air quality 84
Measuring indoor air quality 84
8 Bibliography 85
Appendix A 87
Appendix B 89

Summary

Aims of this report

This report presents results and recommendations following research into examples of good practice in ventilation and indoor air quality for new homes. The aim is to inform and support the work of teams involved in procuring, designing and building low energy homes, by providing clear information highlighting good practice in ventilation and indoor air quality.

Following evidence of some significant problems with indoor air quality in new low energy homes (Crump D July 2009) (McKay S March 2010) (Good Homes Alliance 2010), this study aimed to identify lessons from examples of good practice.

The main question posed for this investigation was:

What lessons are emerging from monitored new low energy homes, regarding good ventilation performance and indoor air quality?

In order to answer this main question several sub questions were set:

- *What evidence is available, regarding the real performance of new low energy homes?*
- *What evidence is there of good indoor air quality and ventilation performance in new low energy homes – data and anecdotal?*
- *What evidence is there for how design, construction, commissioning and operation have influenced indoor air quality and ventilation performance?*
- *What further work is needed in order that this question might be answered more effectively?*

Indoor air quality and ventilation in low energy homes

Where energy efficient homes are designed to reduce heat losses through improved airtightness, risks of inadequate ventilation are possible. Previously, the 'draughtiness' of the building envelope would provide a constant flow of air through the property, but would also allow uncontrolled ventilation heat loss.

As Building Regulations Part L pushes tested air permeability of buildings below $10m^3/m^2/hr@50Pa$, the provision of adequate controlled ventilation becomes increasingly important, through either natural or mechanical means, or a combination of both. Part F of the Building Regulations provides requirements for how this is achieved. However, an emerging body of evidence (Crump D July 2009) (McKay S March 2010) suggests that serious problem with ventilation and indoor air quality, are evident in many new homes, caused by ineffective ventilation systems.

In response to this, the Good Homes Alliance (GHA) held an event calling for evidence of the real performance of ventilation and indoor air quality in new low energy homes (Good Homes Alliance 2010). The evidence presented from developers, housing associations and researchers suggested that there are problems with both passive and active systems, and that problems are very significant and occur at multiple stages of the process.

What was done

Having identified significant problems with indoor air quality in low energy homes, the next step was to address practical solutions. This GHA research has aimed to gather evidence from examples of occupied homes, where indoor air quality has been shown to be good, and to extract useful lessons. A summary of the emerging evidence and lessons is presented here.

What was found

The following conditions were set in order to identify examples of good ventilation practice:

- Sufficiently airtight to require the provision of controlled ventilation to ensure good indoor air quality
- Providing measured data demonstrating good indoor air quality

Very few dwellings were found that met these criteria. Without consistent data from a large number of dwellings, the findings presented here can only lead to limited conclusions. However, the data and experiences revealed by examples do provide some understanding for how good indoor air quality was achieved. This report also presents comments on the scope of research undertaken at this time, the limitations of the data collected and further work that is needed.

Despite limitations, the evidence presented in this report indicates that it is possible to achieve good indoor air quality in low energy homes. It also stresses how important it is that ventilation be considered a priority from the earliest stages of the design process, in order to ensure good, healthy indoor conditions for the eventual occupants, while providing an energy efficient building.

Recommendations

Recommendations have been made, regarding the following:

1. Improvements to practice at each stage of a development: design, construction, installation and commissioning, occupancy, operation, and maintenance.

2. The measurement and learning activities that are needed to inform the various stages of the process

3. Implications for legislation and mainstream construction

4. Research that is needed to develop our understanding further, and to produce best practice guidance for good indoor air quality in new low energy homes.

1 Introduction

1.1 Sustainable homes

The **Good Homes Alliance** is a group of housing developers, building professionals and other industry supporters whose aim is to close the gap between aspiration and reality by showing how to build and monitor homes, which are sustainable in the broadest sense. Recent priorities have focussed on:

- low energy use
- health and well-being
- proof of performance

These three aspects clearly relate to the question set for this research.

The GHA considers the design and construction of good homes in terms of the following physical characteristics:

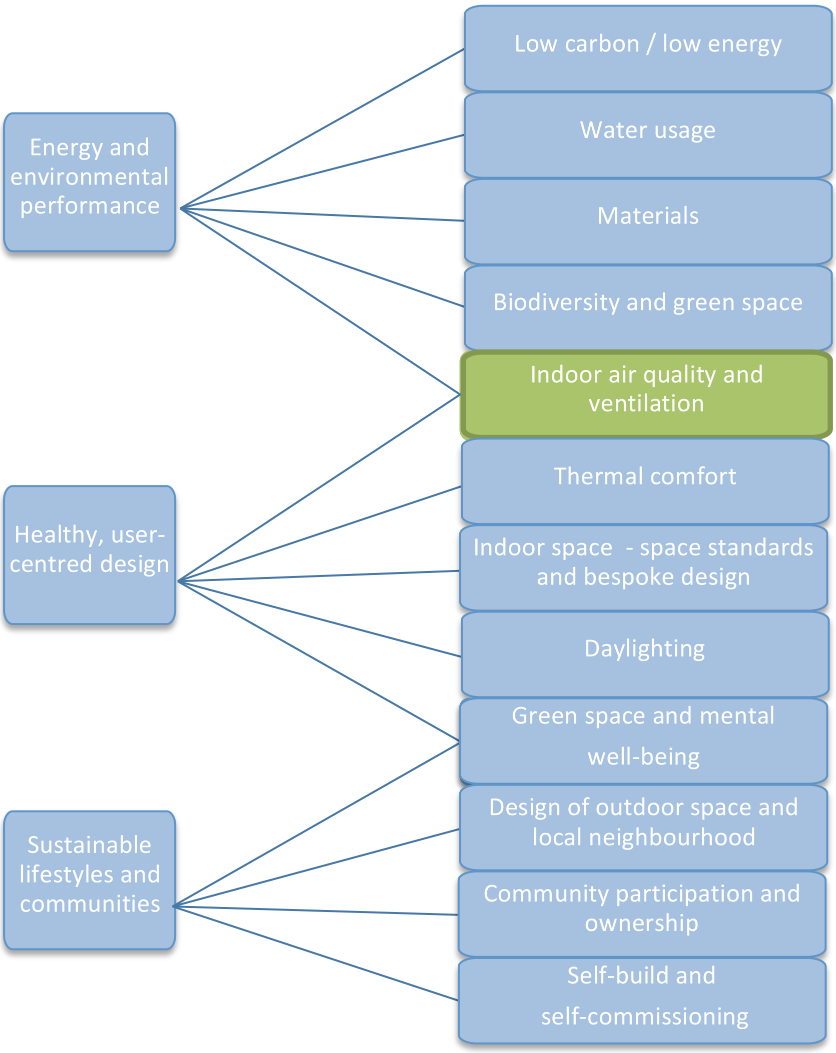


Figure 1–A Schematic of GHA constituents of a 'good home'.

These characteristics are considered at all stages of the process, through planning, procurement, design, construction, operation and maintenance. Additionally, monitoring and feedback are considered crucial in order to gather evidence and learn what works and what does not.

The focus of the work presented in this report is 'Indoor air quality and ventilation' in new homes. However, it should be remembered that no one aspect can really be considered in isolation. Other aspects such as the drive for lowering energy use, the materials that are specified, the form of the building, and the buildings relationship with the outside space, also have significant influences on indoor air quality.

1.2 Low energy homes

Recent years have seen the mainstream construction industry focus on the reduction of energy use in new housing. New dwellings are built to regulations that require greater energy efficiency. The heating load of a home is minimised by reducing the loss of heat through the building fabric, through greater insulation, and reducing uncontrolled ventilation losses by making the envelope more airtight (alongside the provision of a purpose provided ventilation system).

On 10th November 2010, the Good Homes Alliance held an event (Good Homes Alliance 2010), co-hosted by the Zero Carbon Hub and National Housing Federation entitled 'Health & Well-Being for Occupants: Ventilation, Condensation & Internal Air Quality'. At this event, attendees and presenters were asked to describe the issues they faced in low energy, airtight dwellings with regards to occupant comfort and indoor air quality. The sources of the various problems identified are presented in the following table:

Table 1-I Problems arising with types of ventilation and when these arise.

	Design	Installation	Operation
Natural ventilation	Dependence on design of building form and occupant operation.	Systems should be simpler than mechanical, but good installation is crucial.	High dependence on occupant behaviour and operation. Lack of understanding.
Mechanical ventilation	Lack of skills and experience designing complex systems for homes	Lack of skills and experience installing and commissioning complex mechanical systems in homes	Complexity of systems and lack of information for occupants.

The majority of problems presented at this event related to:

- A greater risk of natural ventilation providing insufficient ventilation in airtight homes

- Mechanical ventilation being complex, leading to incorrectly sized fan units, poor installation and commissioning practices and lack of user understanding of the system.

One of the main causes of problems with active systems seems to stem from the relatively recent introduction of complex services within residential buildings. While the non-residential sector has for many years used complex services, lessons cannot always be directly transferred to a sector with such different use profiles. The residential sector has very little history in the UK of experience in design, installation or use of these systems. There is also a lack of integration of ventilation strategies with other aspects of the home, and pressures on space mean that any services provided are often poorly located resulting in misuse, poor maintenance and then, inefficient operation. This growing mechanisation of the home has not been fully accepted in the UK, and occupants are not always aware of the benefits of mechanical ventilation systems, switching them off or failing to carry out routine maintenance.

Ducting layouts are a particular challenge for both active and passive systems. Longer lengths and more bends will slow down the flow of air through a ventilation system. If the ventilation strategy is not considered within the design process, then ducting layouts may prove to be too long or complex to deliver good ventilation.

1.3 Indoor air quality and healthy homes

There is a substantial body of research linking the negative health effects of poor indoor air quality and pollutants in the home. A review of the literature can be found in *Indoor Air Quality in Highly Energy Efficient Homes* (Derrick Crump 2009).

The impact of indoor air quality on the health of an individual is dependent on:

- The toxicity of the pollutants
- **The concentration of pollutants in the indoor air**
- The time the person is exposed to pollutants in the indoor air
- The vulnerability of the person

This investigation focuses on the concentration of pollutants in the indoor air. Only the toxicity and concentration of these pollutants can be influenced by the building. While the toxicity of the pollutants is dependent on the source, the concentration of pollutants in the indoor air is dependent on:

- The production rate of pollutants
- The dilution rate of those pollutants.

Both production and dilution are influenced by a number of aspects of the building: the design, location, fabric, services, external conditions and occupant behaviour. Some of the many variables influencing indoor air quality are presented in the following two tables.

Table 1-II Variables influencing the production of pollutants

Aspect	Variables
Building design & location	Openings onto polluted external areas, position of pollution sources within the building etc. Eg ground floor flat on a main road.
Building fabric	Emissions from construction products, furnishings etc, moisture permeability of the fabric
Building systems	Emissions from gas or biomass heating and cooking systems
External conditions	Pollution levels in external air (eg urban areas, close to roads), temperature and moisture content of external air, wind pressure.
Occupant behaviour	Occupant density and activities (physical activity, washing, cooking, use of chemicals etc)

Table 1-III Variables influencing the dilution of pollutants

Aspect	Variables
Building design and location	Building orientation and form, and influence on ventilation strategy. E.g. Dual aspect, Passive Stack etc.
Building fabric	Uncontrolled ventilation, which is more significant in in leaky buildings.
Building systems	Controlled ventilation systems (MVHR, MEV, trickle vents etc)
External conditions	Filters to air intakes
Occupant behaviour	Door and window opening, interaction with ventilation systems etc

Predicted performance regarding both energy use and indoor air quality, will depend on assumptions about each of these variables, some of which are guided by regulation.

A developer and design team can control the building design, location, fabric, systems, and exposure to external conditions to varying extents. Though they may attempt to influence occupant behaviour, they cannot control it. Additionally, interactions between each of these variables will inevitably complicate the picture. Examples of this are revealed later.

Though various publications have explained the difficulties of ventilating airtight homes successfully, few have provided evidence for how these problems can be successfully avoided. The research presented in this report seeks to find examples of low energy homes with evidence of good indoor air quality and to understand how this has been achieved. It is hoped that this will inform those commissioning and building low energy homes, to current building regulations and beyond, and thus improve ventilation provision for those homes.

In order to undertake a conclusive study of indoor air quality in low energy homes, each of the variables identified in the pollutant production and dilution tables (Tables 1-ll and 1-lll) would need to be recorded over a significant period of time, in a large number of properties. This study is not able to undertake such a task. Instead, it reviews the evidence that is already available, regarding concentrations of Carbon Dioxide (CO_2) and moisture (relative humidity, RH) in low energy homes. Using this evidence as the basis for judging whether the indoor air quality of these dwellings is 'good', experiences and lessons are drawn from reports and interviews revealing possible causes of the evidently good indoor air quality.

2 Ventilation and Indoor Air Quality

This section sets out some of the background to ventilation and indoor air quality. It also explains the indicators of good indoor air quality used for this investigation, and why particular levels were chosen.

This report does not detail the health impacts of indoor air quality. For a more detailed review on the research on indoor air quality and occupant health and well-being, please see the NHBC Foundation's report *Indoor Air Quality in Highly Energy Efficient Homes* (Derrick Crump 2009)

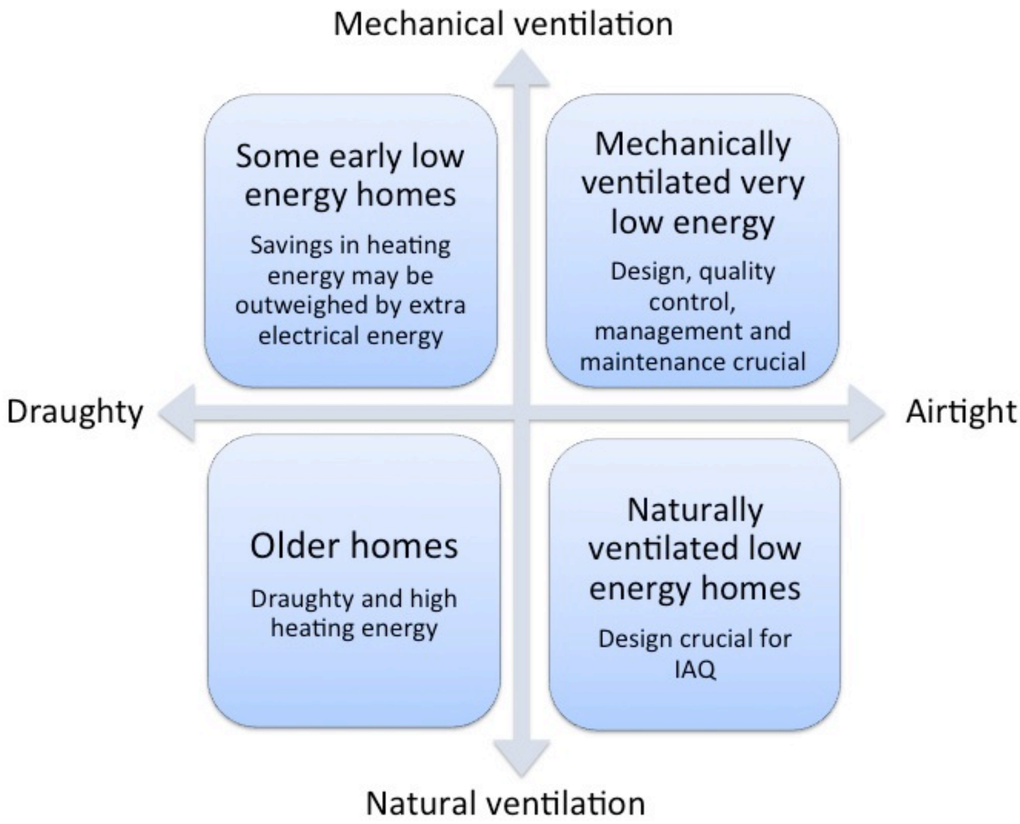


Figure 2–A The influence of airtightness and ventilation on comfort and energy use.

Ventilation is necessary in order to maintain the indoor air quality of a dwelling.

CIBSE Guide B ((CIBSE 2005), p.2-28) states that:

> *Fresh air supplies within dwellings are necessary for:*
>
> - *The health and safety of the occupants*
> - *The control of condensation, often the dominant pollutant arising from moisture generated by cooking, washing and clothes drying*
> - *The removal of odours*
> - *The removal of pollutants such as VOCs*
> - *The removal of allergens arising from dust mites*
> - *The safe operation of combustion appliances*

Ventilation is provided through both uncontrolled means (a leaky building envelope), and controlled means (either natural or mechanical).

It is recommended that the ventilation strategy should achieve a total (uncontrolled plus controlled) whole house ventilation rate of 0.5 – 1 Air Changes per Hour (ACH), or rapid extraction of moisture at source, in order to keep relative humidity from exceeding 70% for extended periods. Approved Document F recommends that a minimum of 8 litres of fresh air per second be provided per person in occupied spaces. A number of ventilation strategies are available in order to achieve this.

Ventilation is also a significant heat loss route, and influences the amount of space heating energy used.

2.1 Regulation

In order to control the heat lost through ventilation, the fabric leakiness (or permeability) causing uncontrolled ventilation must be reduced.

Building Regulations Part L sets regulations relating to the conservation of heat and power. This includes an upper limit for a building's air permeability, intended to reduce uncontrolled ventilation heat loss in new dwellings. Approved Document L1A (ADL1A (HMGovernment 2010)) lists the worst acceptable standard of fabric air permeability as $10m^3/m^2/hr$@50Pa (ADL1A p.15, table 2). It also sets out requirements for pressure testing necessary to demonstrate compliance (ADL1A p.19).

Reductions in uncontrolled ventilation heat loss have resulted in reduced heating demand. However, once uncontrolled ventilation is reduced, sufficient ventilation must be provided through controlled means.

In order to ensure sufficient levels of ventilation, Part F of the Building Regulations (ADF (HMGovernment 2010)) sets standards relating to ventilation provision and performance (ADF, p.19). This sets requirements for dwellings with different levels of air permeability, and different ventilation strategies. Compliance can be met through one of these means:

1. Meeting specified ventilation rates
2. Following the specified system guidance
3. Using a system that is demonstrated to achieve the specified indoor air quality criteria

The most recent Part F edition has introduced measures to deal with some of the problems arising with mechanical systems. The Domestic Ventilation Compliance Guide (2010) is referred to by ADF for guidance on installation, testing, commissioning and provision of information. There are requirements set out for commissioning and onsite measurement of airflow rates for mechanical ventilation systems, evidence of which must be presented to Building Control. Additionally, sufficient information about the ventilation system and its maintenance must be provided to the occupants.

The intention is that Part L sets requirements to reduce carbon emissions caused by energy demand in new homes, and Part F ensures that air quality is good in new homes. However, there is as yet insufficient evidence from the real operation of new homes, to know for certain whether either of these measures are effective.

This investigation aims to gather evidence and begin the discussion around these issues.

2.2 Ventilation strategies

A number of different ventilation strategies are commonly used in new homes, and are able to provide good indoor air quality. However, effective design, installation, and operation will be crucial to good indoor air quality and minimised energy use. The following is based on CIBSE Guide B 2.3.10.3 (CIBSE 2005) and Building Regulations *Approved Document F – Means of Ventilation* (HMGovernment 2010).

Passive stack ventilation (PSV)

Vertical ducts leading from vents in kitchens and bathrooms to ridge or tile terminals. Stack and wind effects draw moist air out of the building, and fresh air in through a leaky fabric and trickle vents etc.

Air quality – Good, if adequately controlled, but can be reliant on wind, pressure differences and leakiness of fabric.

Energy use – No electricity use, but reliant on effective control to reduce ventilation heat loss.

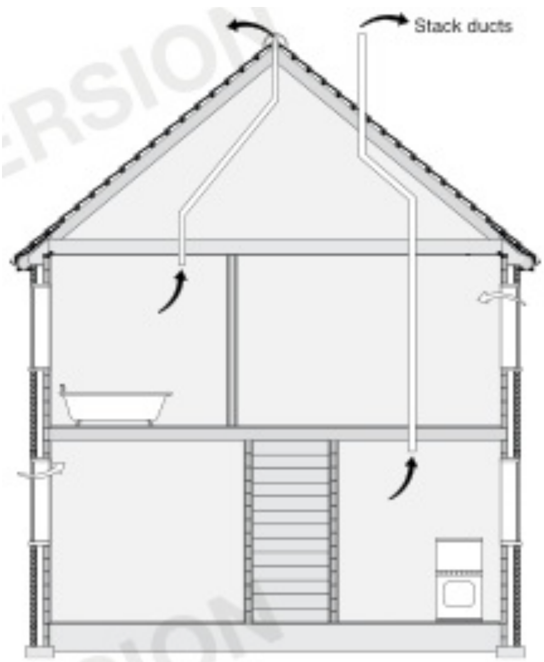


Figure 2–B Passive Stack Ventilation. This diagram is extracted from Building Regulations Part F (HMGovernment 2010) and courtesy HM Government

Local extract fans

Rapid extraction of moisture etc from kitchens and bathrooms. Control may be occupant, light switch, humidity or a combination. Fresh air delivered through trickle vents and leaky fabric.

Air quality – Dependent on the leakiness of the fabric etc. Prone to user tampering due to high perceived running costs and noise of the fans.

Energy use – Uses electricity, but low power fans and intermittent use minimise this. Ventilation heat loss is still an issue but reduced due to greater control. This heat loss can be reduced further with use of a heat recovery room ventilator, recovering around 60% of heat from outgoing air.

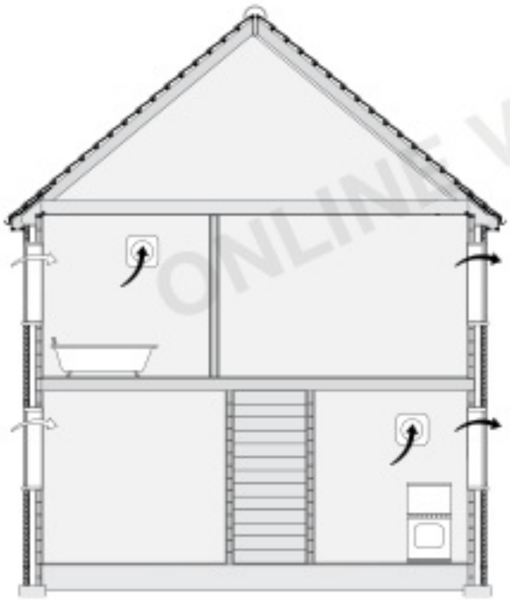


Figure 2–C Background Ventilators and Intermittent Extract Fans. This diagram is extracted from Building Regulations Part F (HMGovernment 2010) and courtesy HM Government.

Mechanical supply ventilation

Fresh air is supplied through a fan unit in the roof space, which pre-heats and filters it. The leakiness of the fabric or vents provides extract routes.

Air quality – Depends on the layout of the building (extra fans may be necessary for more distant rooms). Anecdotally considered an effective means of condensation control, but there is no data available to support improvements in air quality. Perceived high running costs and noise can cause occupants to tamper with the system.

Energy use – There is limited research into performance.

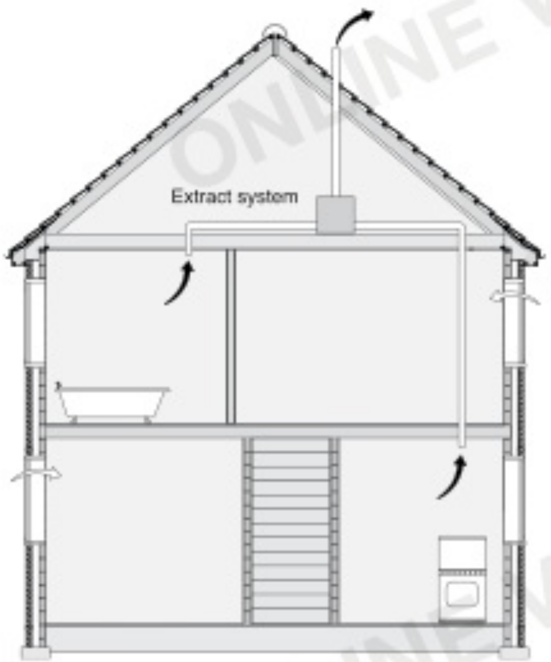


Figure 2–D Continuous Mechanical Extract. This diagram is extracted from Building Regulations Part F (HMGovernment 2010) and courtesy HM Government.

Whole house mechanical ventilation (with or without heat recovery)

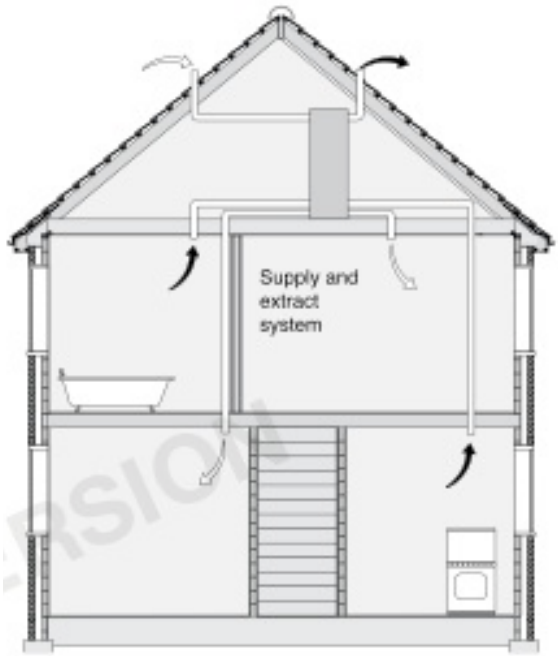


Figure 2–E Continuous Mechanical Supply and Extract with Heat Recovery. This diagram is extracted from Building Regulations Part F (HMGovernment 2010) and courtesy HM Government.

Whole house mechanical ventilation consists of combined extraction of warm moist air in kitchens and bathrooms, and supply ventilation ducted to other habitable rooms. With the inclusion of heat recovery in very airtight homes (max 4ACH@50Pa), Mecahnical Ventilation with Heat Recovery (MVHR) can also reduce the heating load

Air quality – Capable of reducing condensation and other pollutants significantly, but reliant on informed design, installation and operation.

Energy use – Controlled system and airtight fabric can reduce ventilation losses and heating energy significantly, as in Passivhaus buildings. However, electric fans are needed to keep systems running constantly. More complex systems can increase the risks of reduced efficiency, associated with inadequate installation, commissioning and operation.

Wind-Assisted Passive Heat Recovery System

(Passive Ventilation with Heat Recovery – PSHR) A wind-assisted passive heat recovery system was designed by ZEDFactory and used on one of the examples sites described later (BedZED). This diagram illustrates how the wind cowl operates. Placed on the roof, it utilises natural air pressure differences to draw air in and out of the building, through a heat exchanger. The wind cowl forms part of a whole house system, designed to supply ventilation to the entire building.

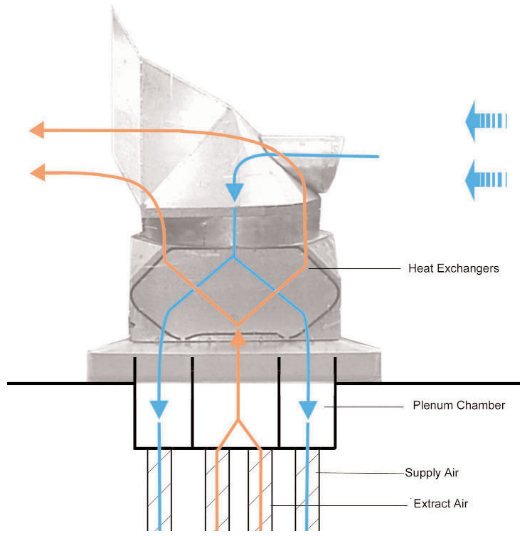


Figure 2–F Wind Cowl, Part of a Wind-Assisted Passive Heat Recovery System. Diagram courtesy ZEDFactory.

All of these strategies have the potential to deliver good indoor air quality and save energy. However, what is actually achieved in a real building will depend to a large extent on the quality of the design, installation, maintenance and operation carried out.

2.3 What is good indoor air quality?

According to Bluyssen (Bluyssen 2009, p.66) indoor air quality is dependent on several parameters:

> *For indoor air quality, the exposure of an individual to pollutants present in a space is significant. This exposure can be defined as the concentration of the pollutants over time expressed in μg/m^3. The concentration of pollutants depends upon several parameters:*
>
> - *The production of the pollutants in the space expressed by the emission rate of a pollutant (substance) in μg/s or μg/s per m^2 of surface area of source;*
> - *The ventilation rate of the space in which the pollutants are produced, expressed in m^3/h or l/s;*
> - *The concentration of the pollutants in the ventilation air, expressed in ppm or μg/m^3*

This report concentrates on two pollutants only: moisture and carbon dioxide. It is beyond the scope of this study to consider other pollutants such as VOCs, Radon etc, which do pose significant risk to human health in high concentrations (Crump D, July 2009, pp. 9-12), but for which data is not available in sufficient quantities. Furthermore, this research is concerned with indicators of air quality relating to effective ventilation, and not with the sources and control of individual pollutants.

Carbon Dioxide

BS EN 15251:2007 (BSI 2007), Indoor Environmental Input Parameters[i], states that:

> *Air quality can be evaluated in buildings where people are the main pollution source by measuring the average CO_2 concentration in the building, when building is fully occupied. This can be done either with representative samples of room air or by measuring the concentration of the exhaust air... Only if specific complaints (e.g. smell, sick building symptoms) persist and ventilation measurements show that the requirements for fresh air supply are met should measurements be made of specific pollutants (e.g. formaldehyde, other Volatile Organic Compounds, fine dust (PM 10 or PM 2.5)).*

This recommendation is a practical one in that CO_2 levels are relatively easy to measure and this can be done at relatively low cost. This investigation, therefore, uses CO_2 as a proxy for all airborne pollutants. CIBSE Guide B (CIBSE 2005, p.2-15) states that:

*Within the UK, a **CO_2 level of 800 to 1000ppm** is often used an indicator that the ventilation rate in a building is adequate, which would appear to equate to a fresh air ventilation rate of 8l/s per person.*

CO_2 does not itself pose any risk at these levels, but indicates the ventilation is sufficiently high to dilute other pollutants to a safe concentration. However, much greater levels of ventilation, resulting in a lower CO_2 concentration may indicate an overly ventilated space and, thus in the case of mechanical ventilation, excessive energy used by the system.

Table 2-I Expectations of carbon dioxide levels.

Carbon dioxide	CIBSE Guide B, 2005	ASHRAE
Outside air	Approx. 350ppm	
As an indicator of adequate air quality	800-1000ppm	under 1000ppm
As a pollutant	5000ppm (8 hours av.)	2500ppm

Relative Humidity

Relative humidity levels indicate the risk of condensation, mould growth and resulting adverse health reactions. A review of the health effects of relative humidity in indoor environments (Arundel A V n.d., p. 351-361) recommends that:

"The majority of adverse health effects caused by relative humidity would be minimized by maintaining indoor levels between 40 and 60%".

The role of air and surface temperature should also be considered. Warm air can hold more moisture than cold air, and therefore warm air with a low relative humidity that is suddenly cooled may experience a rise in relative humidity.

Relative humidity also has an important role in the risk of interstitial condensation and subsequent damage to the building fabric. However, this issue is not discussed here.

Table 2-II presents the recommendations of various bodies regarding relative humidity levels.

Table 2-II Guidance on relative humidity from various sources

Evidence of Moisture	Building Regs ADF1 (HMGovernment 2010)			BSI BS5250:2002 (BSI 2002)	ASHRAE (ASHRAE n.d.)
Visible mould	Not visible				
	1 month moving average	1 week moving average	1 day moving average		
Surface water activity (1=100%)	0.75	0.85	0.95		
Air relative humidity	65%	75%	85%	70% (specified as level above which condensation and mould growth occurs)	45% - 55%

As a result of a review of the various guidance a **relative humidity level generally falling between 40% and 60%** has been selected for this investigation, as a further indicator of 'good' indoor air quality.

2.4 Measuring ventilation and indoor air quality

Problems with predicting indoor air quality

If air leakage is greater than predicted, the resulting ventilation rate will be greater. This can have a positive impact on the indoor air quality if the outdoor air is not polluted, but will cause a greater ventilation heat loss, and therefore greater heating energy demand than predicted. However, air leakage that is lower than predicted can reduce uncontrolled ventilation to a level that could cause problems with indoor air quality.

As well as problems with predicted air leakage, the performance of purpose provided ventilation may also not meet design expectations. Problems can emerge with both natural and mechanical systems, due to poor design, installation, operation or maintenance. These too can lead to higher or lower than predicted ventilation rates, and influence delivered indoor air quality and energy savings.

Measuring airtightness

Air permeability, or airtightness measurement of the building tells us how much ventilation is due to the draughtiness or leakiness of the building envelope.

Methods for measuring air permeability have been shown to vary, depending on outdoor conditions and air pressure etc.

Air permeability is measured according to The Air Tightness Testing and Measurement Association Technical Standard L1 (ATTMA 2010), which is based on the British standard BS EN 13829:2001 and describes appropriate pressure testing in order to satisfy Part L of Building Regulations for dwellings. Though this is the standard technique, either depressurisation or pressurisation can be used. However, some organisations advise to do both and take the mean of the two results (Technology Strategy Board 2011). Results from each test can differ, depending on the direction and effectiveness of window seals and ventilation dampeners, as well as external conditions.

Details of using the decay of the concentration of CO_2 levels to characterise the background ventilation are available in a paper by Roulet and Foradini (2002) (Roulet C.A. 2002). Additionally, the PerFluorocarbon Tracer (PFT) gas technique can be useful particularly in occupied buildings (Leeds Metropolitan University n.d.)

Measuring indoor air quality

This investigation gathers measured data regarding CO_2 and relative humidity (RH) levels in new homes. However, this data comes from various sources, and in many cases has been measured in different ways.

There is no one specified industry standard for measuring indoor air quality. However, ***BS EN 15251:2007 Indoor Environmental input parameters (9.2.3***) (BSI 2007) states the following:

> *Measurements shall be made where occupants are known to spend most of their time, preferably at head level during typical high load conditions.*
>
> > • *CO_2 measurements should preferably be made under winter conditions, as normally fresh air supply is lowest during the colder months (limited use of operable windows, partly closed facade shutters due to draught risk).*
> >
> > • *In some cases momentary measurements at 'worst case times' (e.g. end of the morning or end of the afternoon in for example an office or school) might be sufficient.*
> >
> > • *In larger buildings not all rooms need to be evaluated and measurements in only 5 or 10% of the rooms (representatively chosen) might be enough.*

For monitoring of indoor air quality, the BRE document, *A Protocol For The Assessment Of Indoor Air Quality In Homes And Office Buildings* (Crump, et al. 2002) lays out a sampling strategy, as does *ISO 16000 Indoor Air – Sampling Strategies* (ISO 2004). ISO 16000 Part 1 giving general guidance on a sampling strategy. These have been referenced by one of the researchers whose work is included here, Ian

Mawditt. He notes that the published standards and protocols need to be tailored to suit any study that they are used for (Mawditt 2006).

The TSB Building Performance Evaluation Guidance for Project Evaluation recommends the following for collecting data on internal and external environmental conditions:

> *During long term monitoring tests, internal and external temperature, relative humidity and CO_2 readings should be captured by a suitable data acquisition system.*
>
> *Three sensors (temp and humidity combined) internally – main living area, master bedroom and close to thermostat (not in areas of high humidity). When MVHR systems are installed, at least one of the sensors (or an additional one) should be in an area of high humidity. At least one CO_2 sensor should be used. However, these are now often combined with temperature and humidity in which case three readings for each parameter will be captured.*
>
> *One external sensor in sheltered area out of direct sunlight. Readings taken at 5 min intervals over full duration of monitoring period.*

External Conditions

Microclimate and external conditions, including pollution will have a bearing on the internal air conditions. The TSB (Technology Strategy Board 2011) recommends taking data from the local weather station and using this in the analysis and interpretation of building performance. More immediate conditions should also be measured:

- *During long terms monitoring tests, internal and external temperature, relative humidity and CO_2 readings should be captured by a suitable data acquisition system.*
- *One external sensor in sheltered area out of direct sunlight. Readings taken at 5 min intervals over full duration of monitoring period.*

None of the reports consulted for this investigation contained details of climatic conditions. Some include external conditions data, which have been included for information. But no analysis of its relationship to the internal conditions has been made. Where relevant comments have been made by researchers, these are included in the text describing experience on that site.

Perceived indoor air quality

An investigation into ventilation and indoor air quality is concerned primarily with the health and wellbeing of the building occupants. As such, it is important that appropriate value is given to comments made by the occupants on how ‘good’ they think the indoor air quality is. However, while occupants may smell some pollutants, or feel stuffy, they will not be able to detect many toxic pollutants, and opinions about comfort can vary between individuals.

Where available, this investigation presents gathered feedback from occupants regarding indoor air quality, comfort and health. However, much of this is based on the perceptions of individuals, which can vary significantly, and is therefore limited in terms of how it can be interpreted. Examples of instances where perceived indoor air quality appears to contradict measured results, are presented and discussed in a later chapter.

Assessment of occupant satisfaction, involving surveys and interviews of building users, is an essential part of Building Performance Evaluation (BPE) (also known as Post Occupancy Evaluation (POE)).

In the research reviewed for this study, no standard method seemed to have been used to gather information on occupant perception of indoor air quality. The Building Use Survey (BUS) tool is one means, used by a number of researchers and recommended by the TSB for the Building Performance Evaluation programme (Technology Strategy Board 2011). The BUS is a version of a tool developed by the Useable Building Trust. It covers various aspects of the occupant's experience of their home and includes characteristics of the air (e.g. freshness and odour), as well as control over ventilation and heating, and healthiness of living in the building (BUS Methodology 2010)

Measuring Performance of Ventilation Systems

The TSB recommends measuring flow in MEV and MVHR systems in the following way:

- *Measure flow with an airflow device, typically a 100mm vane, fitted into a plastic capture hood, or alternatively a low flow collector hood (for larger outlet diffusers), calibrated in an ISO 17025 accredited test house. In both cases it is critical that the measurement devices are calibrated for volume flow* ***not*** *air velocity.*

Analysis of measured indoor air quality data

It is possible to use measured CO_2 levels, temperatures and moisture levels as the basis for calculations of the actual ventilation rate in a building. However, this work does not attempt such a task. Some of the research examined for this does include such calculations, or measured ventilation flow rates, which have been presented where available.

However, this work relies on the measures of CO_2 and RH as **indicators** of indoor air quality, and successful ventilation practice. Due to limitations of this work and the variation in the data collected, it does not attempt to evaluate the ventilation rates.

3 Our Methodology

In order to fully assess the influences on indoor air quality of occupied dwellings, all of the variables which influence concentrations of pollutants (identified in Tables 1-ll and 1-lll) would need to be recorded . This would have to be carried out in a large number of dwellings over a sufficient time period, and in a consistent manner. However, apart from the cost and difficulty of such a task, even this reductionist approach would be limited due to the complexities caused by relationships between these variables. As a result, drawing meaningful conclusions may well prove to be impossible.

This investigation did not undertake such a task. Instead, the aim was to gather indicative data and emerging lessons, from available research that has already been carried out on real new low energy homes, regarding indoor air quality. Through a largely qualitative approach, using a review of existing literature and case studies, it is hoped that an informed discussion of the practical measures needed for good indoor air quality in new low energy homes can begin.

3.1 GHA Working Group

A working group was set up to discuss ventilation and indoor air quality. This was made up of interested GHA members and experts in building performance. The Working Group shared experience on the subject, recommended the path of the research reported on here and were able to suggest sources of data and detailed information. An interim report and draft versions of this report were given to the group for review and comments.

3.2 Search for Proven Good Indoor Air Quality

A search for low energy homes with proven good indoor air quality was undertaken. The types of evidence that were sought are presented in the table below.

Table 3-I Problems associated with ventilation and evidence of their presence

Problem	Evidence		
	Monitored data	**Occupant feedback**	**Measured tests**
Overheating	Temperatures	Thermal comfort	
Condensation & mould growth	Relative humidity levels	Moisture, mould and visual evidence	
Ventilation rates	CO_2 levels	Stuffiness	Measured ventilation rates

Evidence of the indoor air quality and performance of the ventilation strategy was formed by monitored data relating to CO_2 levels, relative humidity and internal temperature within the homes, as well as occupant feedback.

3.3 Selection criteria

Three criteria were set as conditions for dwellings that could be used for this study. The aim was to examine the performance of airtight dwellings that provided evidence of good indoor air quality, plus information on how that might have been achieved. It should be noted that the criteria below do not provide definitions of 'airtight' or 'good indoor air quality'. But are selected as starting points in order to identify dwellings that are most likely to inform this study.

Dwellings for this study were selected based on the following criteria:

- Relatively low air permeability – Design target of $5m^3/m^2/hr@50Pa$ or lower, and achieving $7m^3/m^2/hr@50Pa$ or lower in tests.
- 'Good' indoor air quality – available monitored data suggesting carbon dioxide levels largely lie between 800 and 1000 ppm, and/or relative humidity levels largely between 40% and 60% (see 2.3)
- Available information regarding the design process, construction, commissioning and occupant feedback.

It should be noted that these criteria are deliberately loose, to widen the net as far as possible. With a larger pool of possible dwellings, these criteria could have been more closely defined, requiring that the 'good indoor air quality' indicator values were met as a specific average, or for a certain percentage of the time.

3.4 Sources of Information

Initial sources included a literature list compiled by the Zero Carbon Hub, various selections of case studies including the Department for Communities and Local Government's (CLG) Code for Sustainable Homes Case Studies volumes 1, 2 and 3; Energy Saving Trust case studies; GHA Low Carb 4 Real Design Case Studies; plus Passivhaus Conference Proceedings (various years) and contact with the network of GHA members. Details of reviewed sources can be found in Appendix A

3.5 The data and information sought

Each of these sources was reviewed as follows:

- Review of each source to identify papers and reports that may be useful
- Review of each paper, report or other material
- Presenting details of possible examples and evidence of performance.

The information was narrowed down, by filtering according to the following criteria:

1. Does the paper or report refer to an example of housing?

2. Does the housing design meet one of the following performance standards:
    a. Part L 2010 building regulations
    b. Code for Sustainable Homes level 3 or above
    c. Airtightness targeted or tested at $5m^3/m^2/hr@50Pa$ or lower (or equivalent)
3. Is there mention that evidence of building performance is being gathered?
4. Is there mention that evidence of Ventilation and Internal Air Quality performance is being gathered in any of the following forms?
    a. Using qualitative methods - surveys, anecdotal, or other evidence
    b. Using quantitative methods – measurements and monitoring of internal air quality and/or ventilation system performance
5. Has the evidence been gathered for sufficient time (over 1 year) to allow for meaningful conclusions to be drawn?

As the study progressed, two of these conditions were relaxed due to insufficient numbers of suitable properties. The initial limit of $5m^3/m^2/hr@50Pa$ was relaxed to $7m^3/m^2/hr@50Pa$. This was done as a significant number of the monitored dwellings selected had targeted 5 or below, but on closer inspection, did not achieve this level of airtightness. The requirement for 1 year of monitored data was omitted, due to a lack of available examples meeting this condition.

It should be noted that each example of housing identified relates to a development site. Each site may contain multiple dwellings, or only one. The examples presented in this final report are those that provided sufficient information to inform discussion. The form and detail of the evidence presented here varies, and therefore it is not possible to directly compare between the different examples of practice. It is, however, useful as the basis of discussion and recommendations for further research that is needed in the area.

3.6 How the data and information was analysed

Indoor air quality was classified as 'good' in the following circumstances:

- CO_2 levels do not generally exceed 1000ppm
- Relative humidity generally stayed between $40\% \leq RH \leq 60\%$

The dwellings providing evidence of 'good' indoor air quality in this manner were then investigated further. A review of available reports, presentations and other materials was carried out for each site to gather information regarding variables as: the building design, location, fabric, services, external conditions and occupant behaviour (tables 1-II & 1-III). An analysis of these variables and what influence they might have on 'good' indoor air quality, was supported by further questions raised by email or phone. Where available, such information is presented for each example. However, due to the differing research methods and presentations used by the sources, this cannot create a complete picture for every dwelling.

3.7 Comparability of data

The data gathered for this investigation differs regarding the following:

- Time of year of monitoring
- Length of monitoring period
- Timing of data logging, averaging etc
- Type of sensors, calibration and range etc
- Number of sensors (all rooms or one room only)
- Position of sensors within the room (height, proximity to windows etc)

Additionally, the data may have been analysed in different ways, and therefore, what is presented here is to some extent an interpretation, either by the initial researchers or ourselves. Details of any processing of data that was carried out in order to present consistent data here can be obtained from the authors.

As a result of these variations, the data brought together for this report is not directly comparable between properties. Instead, the intention is to use this data to build a picture of what is being measured and how, to identify examples where indoor air quality is considered to be 'good', and to draw lessons and stories that can inform practice.

3.8 Additional Information

As well as the air quality data, various pieces of information about each site were sought. This information is presented so that the reader can better judge the results of the IAQ testing.

Where it was found, the following information is presented for each dwelling in the next chapter:

- dwelling type (e.g. mid-terrace house, apartment)
- standard achieved (e.g. Ecohomes Excellent, Code for Sustainable Homes Level 3)
- tenure
- construction type
- ventilation strategy
- control strategy (for the ventilation system, e.g. no user control, boost only)
- heating system
- occupancy
- floor area
- external CO_2

The above information is included because they are believed to have some bearing on the resulting ventilation and indoor air quality:

- The standard achieved may indicate the attention given to the airtightness, itself affecting ventilation rates
- The occupancy will affect the production of carbon dioxide within the building
- The construction type will affect the level of moisture in the building fabric, as well as other pollutants.
- The age of the building is important as a building that has not yet fully dried out after construction will initially have higher levels of relative humidity.
- The control strategy will be a factor in the interaction between the occupants and their ventilation
- The heating system can affect draughts and air flow, and feeling draughts, residents may be encouraged to block vents.
- The type of dwelling and floor area indicate of the volume of air. This will affect the dilution of CO_2 and moisture. The perception of occupants of the quality of their indoor environment may also be influenced.
- The external conditions will affect air coming into the building through door and window openings and through the ventilation system in the absence of filtering

Also relevant here is occupant behaviour which will influence levels of CO_2 and moisture. This includes window and door opening, washing, drying and cooking. Some studies reported on here did include occupant diaries. It was beyond the scope of this piece of work to make any analysis of the relationship between recorded behaviours and IAQ. Where the original report makes comment, this is included in the paragraphs for each site below.

With sufficient data, we would expect a reader involved with a new development to be able to find an example that closely matches their own project and thus be informed by the experience of that example. However, due to the low number of proven cases where good IAQ has been achieved, no generalisations can be drawn from the information here.

4 Examples

This section presents the data collected and the stories behind the successful ventilation of homes on each development site.

Seven sites were found to have collected evidence relating to low energy homes, which indicated good indoor air quality. Twenty-one dwellings in total feature below. Amongst these, the dwelling types vary, as do the ventilation strategies.

Table 4-I Examples – 21 dwellings (12 dwelling types across 7 sites)

Name	House types	Construction type	Airtightness ($m^3/m^2/hr@50Pa$)	Ventilation strategy
Arun Crescent	6 x 3-bed terraced houses	Timber frame	1.88-1.96	Mechanical Ventilation with Heat Recovery (MVHR)
BedZED	1 x apartment 1 x 3-bed terraced house	Heavy weight masonry - Brick and block fully filled 300mm cavity	1.96 3.11	Passive Ventilation with Heat Recovery (PVHR)
Dunoon, Tigh-Na-Cladach	1 x semi-detached 3-bed 'Code 4' house 1 x semi-detached 2-bed Passivhaus	Timber frame Closed panel timber system	4-5 (estimated) 0.4	Extract fans MVHR
Elm Tree Mews	2 x terraced houses and 1 apartment	Timber frame	6.2 – 6.8	Extract fans in wet rooms
Glasgow Houses	2 x 2.5 storey 4-bed detached	Clay block Timber frame	3 3.2	MVHR MVHR
Stamford Brook 1	2 x 3 storey 3-bed end terrace houses 1 x 2 storey 3-bed mid-terrace house	Masonry	4.5 (mean of 44 properties)	Mechanical Extract Ventilation (MEV)
The Wintles	1 x 4-bed detached 1 x 3-bed detached	Timber frame	6.88 4.64	MVHR Passive Stack Ventilation (PSV)

Presentation

Each development site is presented in turn, given two pages describing the development, common characteristics of the homes and what was learned there. Following this, each dwelling is presented on one page, where the details that vary between the dwellings are shown. Data from the site then follows. As far as possible, the same data is shown here for each dwelling. However, where this is not reported or was not collected, the closest alternative is shown.

Some dwellings have two names. Where this is the case, the name in parenthesis is that in the original research report.

Quantitative Analysis – a warning

Please note, a quantitative comparison of the dwellings was not possible, due to the differing methods and small sample. However, these homes appear to demonstrate evidence of good indoor air quality. Furthermore, an exploration of how these conditions were achieved is a valuable resource to inform discussion and further work in this area. General conclusions are drawn in the chapters following this one.

Other Experience

Additionally, some anecdotal material has informed our conclusions. This is presented following the data-endowed examples.

4.1 Arun Crescent, Billingshurst, West Sussex

Developer	Saxon Weald
Dwelling type(s)	6 x 3-bedroom terraced houses
Date complete	July 2009
Tenure	Rented
Standard achieved	Code for Sustainable Homes Level 5
Air permeability (measured, $m^3/m^2/h@50Pa$)	1.88-1.96 for 4 houses
Ventilation Strategy	Mechanical Ventilation with Heat Recovery (MVHR)
Control Strategy	Remote control
Heating System	Ground source heat pump
Construction type	Timber frame
Dwelling(s) monitored	Whole site

Monitoring details

Method	**where**	**how**	**when**
CO_2	Living room		winter 1: September 2009 – January 2010 winter 2: October 2010 – January 2011 spring: April – June 2011
Relative humidity	Living room		
Internal temperature	Bedroom, living room		

Occupant feedback

Method

Two survey questionnaires were distributed. One was a satisfaction survey distributed by the housing association; the other was focussed on indoor quality and comfort. Two households returned both surveys complete.

Experience[2]

- The ventilation strategy was considered from the start of the project
- The developer felt that Code Level 5 required a high level of airtightness; MVHR was considered the only option for ventilating the homes.
- Quarterly maintenance of the system has been implemented after it was discovered that the manufacturer-recommended annual check was insufficient and monitoring was showing a decline in ventilation rates.
- Occupants can have very different opinions of the same controls and same instructions.

Lessons for future[2]

- Locate the system for easy access in order to clean and change filters
- Maintenance routine needs to be quarterly cleaning or changing of filters
- Design and build contracts to specify rigid ducting. Flexible ducting is cheaper to install but can buckle and block more easily, restricting air flow.
- Occupants need information and guidance. The manual for future developments will include a DVD to demonstrate use of all systems for easy reference by the occupants.

Future developments

Saxon Weald currently has a Passivhaus development (Bryce Lodge, Horsham) on site. Lessons from Arun Crescent have informed the design and process of this new development.

References

1. Arun Crescent: Monitoring Programme – September 2009 – January 2010, Climate Consulting (formerly CEN Services Ltd), (Climate Consulting (formerly CEN Services Ltd) 2010)
2. Telephone interview with Marie Riordan, Saxon Weald, October 2011

Arun Crescent, House 1

Dwelling type	3-bedroom terraced house
Standard achieved	Code for Sustainable Homes Level 5
Air permeability (measured, $m^3/m^2/h@50Pa$)	1.88-1.96 for 4 houses
Occupancy	

Results	what	value winter 1	value winter 2	value spring
CO_2 (ppm)	Mean	-[2]	491	486
	Max.	900	740	897
	Min.	500	383	400
Relative humidity (%)	Mean	-[2]	50.1	47
	Max.	65	61	67
	Min.	45	27	21
Internal temperature (°C)	Bedroom: Mean	23.3	20.1	22.4
	Max.	-[2]	24.5	27.0
	Min.	-[2]	16.4	14.4
	Living room: Mean	22.0	23.2	23.8
	Max.	-[2]	27.3	27.9
	Min.	-[2]	19.5	12.3

[2] Data not reported.

Arun Crescent, House 2

Dwelling type	3-bedroom terraced house
Standard achieved	Code for Sustainable Homes Level 5
Air permeability (measured, m^3/m^2/h@50Pa)	1.88-1.96 for 4 houses
Occupancy	

Results	what	value winter 1	value winter 2	value spring
CO_2 (ppm)	Mean	-[3]	464	499
	Max.	-[2]	743	883
	Min.	-[2]	400	403
Relative humidity (%)	Mean	-[2]	47.8	47
	Max.	-[2]	72	67
	Min.	-[2]	26	18
Internal temperature (°C)	Bedroom: Mean	23.8	19.5	22.0
	Max.	-[2]	23.4	27.8
	Min.	-[3]	12.9	15.7
	Living room: Mean	22.0	22.0	22.6
	Max.	-[3]	26.4	28.8
	Min.	-[3]	13.9	17.1

[3] Fan did not work during this session of testing in this house. No data reported.

Arun Crescent, House 3

Dwelling type	3-bedroom terraced house
Standard achieved	Code for Sustainable Homes Level 5
Air permeability (measured, $m^3/m^2/h@50Pa$)	1.88-1.96 for 4 houses
Occupancy	

Results	what	value winter 1	value winter 2	value spring
CO_2 (ppm)	Mean	-[4]	462	451
	Max.	1050	700	710
	Min.	450	380	400
Relative humidity (%)	Mean	-[2]	42.4	43
	Max.	60	71	64
	Min.	45	20	16
Internal temperature (°C)	Bedroom: Mean	23.5	22.3	23.2
	Max.	-[2]	34.7	27.5
	Min.	-[2]	18.5	15.1
	Living room: Mean	22.6	24.1	23.9
	Max.	-[2]	28.8	28.9
	Min.	-[2]	18.3	12.3

[4] Data not reported.

Arun Crescent, House 4

Dwelling type	3-bedroom terraced house
Standard achieved	Code for Sustainable Homes Level 5
Air permeability (measured, $m^3/m^2/h$@50Pa)	1.88-1.96 for 4 houses
Occupancy	5, with at least one person present throughout the day typically

Results	what	value winter 1	value winter 2	value spring
CO_2 (ppm)	Mean	-[2]	583	549
	Max.	1900	960	1057
	Min.	650	380	403
Relative humidity (%)	Mean	-[2]	46.2	47
	Max.	60	64	65
	Min.	40	25	28
Internal temperature (°C)	Bedroom: Mean	23.4	19.7	23.0
	Max.	-[2]	28.7	28.3
	Min.	-[2]	14.9	19.4
	Living room: Mean	23.1	22.5	23.7
	Max.	-[2]	26.3	28.4
	Min.	-[2]	18.9	14.3

Feedback

Occupant reported satisfaction with the indoor conditions (“fresh and still”), though somewhat too cold in winter and somewhat too warm in summer. They described the initial training/instructions for their ventilation, heating and hot water as excellent and the controls as simple.

Arun Crescent, House 5

Dwelling type	3-bedroom terraced house
Standard achieved	Code for Sustainable Homes Level 5
Air permeability (measured, $m^3/m^2/h$@50Pa)	1.88-1.96 for 4 houses
Occupancy	4, with at least one person present throughout the day typically

Results	what	value winter 1	value winter 2	value spring
CO_2 (ppm)	Mean	-[2]	-[5]	-[5]
	Max.	1900	-[5]	-[5]
	Min.	630	-[5]	-[5]
Relative humidity (%)	Mean	-[2]	57.2	45
	Max.	61	72	65
	Min.	43	30	26
Internal temperature (°C)	Bedroom: Mean	24.1	18.4	22.9
	Max.	-[2]	26.2	28.6
	Min.	-[2]	7.0	16.7
	Living room: Mean	23.2	19.2	24.2
	Max.	-[2]	26.5	28.0
	Min.	-[2]	8.1	13.5

Feedback – Occupant reported dissatisfaction with the indoor conditions ("draughty and stale"). They described the initial training/instructions for their ventilation, heating and hot water as quite poor and the controls as complicated.

[5] Data collection failed.

Arun Crescent, House 6

Dwelling type	3-bedroom terraced house
Standard achieved	Code for Sustainable Homes Level 5
Air permeability (measured, $m^3/m^2/h$@50Pa)	1.88-1.96 for 4 houses
Occupancy	

Results	what	value winter 1	value winter 2	value spring
CO_2 (ppm)	Mean	-[2]	517	464
	Max.	1150	920	720
	Min.	400	387	400
Relative humidity (%)	Mean	-[2]	55.9	49
	Max.	61	72	66
	Min.	35	32	21
Internal temperature (°C)	Bedroom: Mean	23.1	19.4	22.3
	Max.	-[2]	28.2	30.3
	Min.	-[2]	14.1	17.4
	Living room: Mean	22.5	21.5	22.4
	Max.	-[2]	24.2	37.0
	Min.	-[2]	17.3	17.6

4.2 BedZED, Wallington, Surrey

Developer	BioRegional and Peabody Trust
Dwelling type(s)	mixed
Date complete	2000
Tenure	mixed
Standard achieved	Ecohomes Excellent
Construction type	Heavy weight masonry - Brick and block fully filled 300mm cavity
Ventilation Strategy	Passive Ventilation with Heat Recovery (PVHR)
Ventilation Control	No user control
Heating System	District heating

Monitoring details

Method	where	how	when
CO_2	Living room	Non dispersive infrared (NDIR) sensor (5000ppm).	6 min intervals over 7 days, less two 12-hour periods* The data presented is for one 12-hour daytime period.
Relative humidity	Master bedroom, living room and garden, 1000-1500mm above floor level	Gemini TiniTalk datalogger sensors	6 min intervals over 7 days, less two 12-hour periods* The data presented is from the whole 7-day sample.
Internal temperature	Master bedroom, living room and garden, 1000-1500mm above floor level	Gemini TiniTalk datalogger sensors	6 min intervals over 7 days, less two 12-hour periods* The data presented is from the whole 7-day sample.

***Within the sampling period, there were two 12-hour sessions where the ventilation was switched off or the passive ventilation inlets and outlets were sealed**

Occupant feedback

Method

Occupants were asked to rate their perception of the indoor air quality as 'Very good', 'Good', 'Satisfactory', 'Poor' or 'Very poor'.

Experience

- The dwellings were fitted with an innovative, wind-driven, passive ventilation system with heat recovery, produced by ZEDfactory.[2]
- The designers were very involved from the start ensuring ducting was carefully located and installed.[2]
- External CO_2 levels were high during testing. This will have contributed to the levels recorded internally.[2]
- The building fabric had a high level of airtightness, which is thought to contribute to keeping pollutants out of the building.[2]
- The intake for the ventilation system was placed on the highest point of the building, away from pollutants at lower heights, including those from nearby traffic.[3]
- The heat exchanger units have not received maintenance since completion. This is partly due to access being via the roof only. An alternative location could not be found because access via an individual flat was deemed inappropriate or problematic for a communal system.[4]

Lessons for Future

- The effectiveness of the ventilation strategy would need further testing in a smaller dwelling; it relies of pressure difference for driving force and this will be lower in a smaller dwelling.[2]
- Good airtightness is believed to have helped keep the high levels of pollution outside the building from entering.[2]

Future developments

ZEDFactory have further developed this innovative wind-driven ventilation system, and it is in place in Upton on the One Earth Homes. Developed by Metropolitan Housing Partnership to reach Code for Sustainable Homes Level 6, it is understood that monitoring will be undertaken here.

References

1. Ian Mawditt, A Field Investigation of Indoor Air Quality and Ventilation in Low Energy Homes in England (MSc Thesis, 2006)
2. Questionnaire completed by Ian Mawditt, Four Walls, November 2011. Ian carried out performance testing of the dwellings.
3. Questionnaire completed by Asif Din, ZEDFactory Ltd, December 2011. Asif was involved in the design of the dwellings, including the ventilation strategy.
4. Correspondence with Asif Din, ZEDFactory Ltd, February 2012.

BedZED, Apartment

(House 4)

Dwelling type	1-bed apartment
Floor area (m^2)	36
Standard achieved	EcoHomes Excellent
Air permeability (measured, $m^3/m^2/h$@50Pa)	1.96
Occupancy	1

Results	**what**	**value**
CO_2 (ppm)	**Ext.**	670
	Mean	808
	Max.	1295
	Min.	634
Relative humidity (%)	**Mean**	54.1
	Max.	63.3
	Min.	43.3
Internal temperature (°C)	**Bedroom: Mean**	22.9
	Max.	24.8
	Min.	19.5
	Living room: Mean	23.6
	Max.	25.7
	Min.	22.3

Feedback

The occupant perception of indoor air quality was ‘satisfactory’.

BedZED House

(House 5)

Dwelling type	3-bed mid-terrace maisonette
Floor area (m^2)	105
Standard achieved	EcoHomes Excellent
Air permeability (measured, $m^3/m^2/h@50Pa$)	3.11
Occupancy	4

Results	**what**	**value**
CO_2 (ppm)	**Ext.**	690
	Mean	1099
	Max.	1467
	Min.	909
Relative humidity (%)	**Mean**	60.7
	Max.	73.9
	Min.	52.1
Internal temperature (°C)	**Bedroom: Mean**	21.1
	Max.	22.7
	Min.	20.2
	Living room: Mean	18.4
	Max.	22.7
	Min.	16.7

Feedback

The the occupant described the indoor air quality as ‘good’.

4.3 Dunoon, Tigh-Na-Cladach

Developer	Fyne Homes
Dwelling type(s)	1. Semi-detached 3 bed house 2. Semi-detached 2 bed house
Date complete	2009
Tenure	Rented
Standard achieved	1. Low energy 2. Passivhaus
Air permeability (measured, $m^3/m^2/hr$ @50Pa)	1. Not tested – likely to be 4-5 2. 0.4
Ventilation Strategy	1. Mechanical extract in wet rooms 2. MVHR
Control Strategy	1. Light switches 2.
Heating System	1. Electric storage heaters 2. Heat pump

Monitoring details

Method	where	how	when
CO_2	Placed on coffee tables in lounge, 600mm height.	Eltek combined Temp, RH and CO_2.	Ongoing from March 16th 2011. Analysed to June, so far.
Relative humidity	Placed on coffee tables in lounge, 600mm height.	Eltek combined Temp, RH and CO_2.	Estimated from charts March 26th – April 1st.
Internal temperature	Placed on coffee tables in lounge, 600mm height.	Eltek combined Temp, RH and CO_2.	Estimated from charts March 26th – April 1st.

Occupant Feedback

No formal feedback collection. However, comments are recorded below.

Experience

- Good IAQ in the Passivhaus, but higher energy use and lower internal temp than expected.
- Inadequate and missing insulation on MVHR ducting behind unit and in ceiling cavity.
- Additionally, problems with solar hot water and heat pump have emerged, indicating that there is a wider problem with the supply chain for new technologies. Significant immaturity in the supply chain is causing problems with real performance and expected energy savings.
- Original user guide for MVHR was too technical using terms such as 'summer bypass' etc.
- Occupant said air was dry, and watered plants to compensate. Occupant very happy. Energy use low and air quality good.[3]

Lessons for Future

- This has implications for the PH certification process and reliance on the installers to sign off their own work. While this has value in Germany, there may need to be additional quality assurance checks in the UK, at this early stage of applications.
- Installers developed a simpler guide.
- The research team will make recommendations to social housing providers regarding the importance of specification, installation and maintenance plans and information for occupants.

References

1. Paul Tuohy, University of Strathclyde, Presentation for UK Passivhaus Conference 2011, October 2011
2. Paul Tuohy, University of Strathclyde, Phone calls and emails during December 2011
3. http://www.sphc.co.uk/tigh-na-cladach-home-owners-first-experience

Dunoon 1 – Low Energy House

Dwelling type	Semi-detached 3 bed
Floor area (m^2)	
Standard achieved	Low Energy (Code 4 fabric only)
Air permeability (measured, $m^3/m^2/h@50Pa$)	Not measured – likely to be 4-5
Ventilation Strategy	Mechanical extract in wet-rooms
Construction type	Timber frame
Occupancy	2 adults & 3 children

Results	what	value
CO_2 (ppm)	Ext.	374
	Mean	1060.1
	Max.	2231
	Min.	422
Relative humidity (%)	Ext.	85 (typical)
	Mean	-[6]
	Max.	55
	Min.	35
Temperature (°C)	Ext.	3-10
	Mean	-[6]
	Max.	25
	Min.	17

[6] Data not provided.

Dunoon 2 - Passivhaus

Dwelling type	Semi-detached 2 bed house
Floor area (m^2)	88
Standard achieved	Passivhaus
Air permeability (measured, $m^3/m^2/h$@50Pa)	0.4
Ventilation Strategy	MVHR
Construction type	Closed panel timber system
Occupancy	2 adults & 1 child

Results	what	value
CO_2 (ppm)	Ext.	374
	Mean	594.3
	Max.	1384
	Min.	401
Relative humidity (%)	Ext.	85 (typical)
	Mean	-[6]
	Max.	65
	Min.	45
Temperature (°C)	Ext.	3-10
	Mean	-[6]
	Max.	18
	Min.	12

Feedback

Resident said air felt dry and watered plants a lot to compensate. Could have made house warmer if she'd wanted to.

4.4 Elm Tree Mews, New Earswick

Developer	Joseph Rowntree Housing Trust
Dwelling type(s)	2 x terraced houses and 1 x apartment
Date complete	March 2008
Tenure	Social housing
Air permeability (measured, $m^3/m^2/hr$ @50Pa)	6-8 (Original target of 3 omitted from specification)
Ventilation Strategy	Natural ventilation mechanical with extracts in wet rooms
Control Strategy	Humidistat in wet rooms
Heating System	Communal ground source heat pump

Monitoring details

Method	where	how	when
CO_2	1 in kitchen or bedroom.	2 Vaisala GWM25 CO_2 sensor. 2000ppm limit.	Sept 08 - Sept 09 (each dwelling monitored over slightly different period during this time)
Relative humidity	1 in each of living room, hall/toilet, kitchen, bedroom, bathroom.	Eltek GC-10 Temp/RH Transmitter.	ditto
Internal temperature	1 in each of living room, hall/toilet, kitchen, bedroom, bathroom.	Eltek GC-10 Temp/RH Transmitter.	ditto

Occupant feedback

Method

Interviews were carried out with residents

Experience

- No particular measures taken regarding ventilation strategy.
- The original Passive Stack strategy was cut from the specification, to save costs.
- Large houses with low occupancy are thought to be responsible to some extent for the good IAQ.[2]
- Design of bathrooms next to external walls or roof facilitated easy ducting for extract systems.
- In Dwelling 2 (House B), residents had closed most trickle vents and turned off fans in bathrooms and toilet, due to noise. (The resulting air quality was poor, and the data is presented here for information only)

Lessons for future

- House B demonstrated poor IAQ, which was due to occupants switching off extract fans and closing trickle vents. However they did not complain of feeling stuffy. Therefore this problem may not have been picked up without the monitoring. [1]
- Importance of communicating ventilation strategy to occupants
- MVHR used for subsequent projects, due to energy benefits.
- Air permeability of $3m^3/m^2/h$@50Pa was targeted, but not detailed in the spec, so contactors only aimed to better Part L requirements.

References

1. Elm Tree Mews Field Trial: Final Technical Report, Leeds Met CeBE (Dr. Jez Wingfield 2011)
2. Interview with Brian Jardine, Joseph Rowntree Housing Trust

Elm Tree Mews - Dwelling A

Dwelling type(s)	Mid terrace
Floor area (m^2)	107
Standard achieved	
Air permeability (measured, $m^3/m^2/h$@50Pa)	6.34
Ventilation Strategy	Natural ventilation + humidistat controlled extracts in wet rooms
Construction type	Timber frame
Occupancy	4 (unemployed) + 1 dog

Results	**what**	**value**
CO_2 (ppm)	**Annual mean**	558.9
	Max. Monthly Mean	650
	Min. Monthly Mean	400
Relative humidity (%)	**Monthly mean**	50-65
Internal temperature (°C)	**Seasonal mean: Oct-Apr**	17.2
	Jul - Aug	20.0

Elm Tree Mews - Dwelling B

The IAQ in this dwelling is not 'good'. Dwelling B is presented for information only. **See the notes on Page 50 for an explanation.**

Dwelling type(s)	Mid-terrace
Floor area (m^2)	107
Standard achieved	
Air permeability (measured, $m^3/m^2/h@50Pa$)	7.56
Ventilation Strategy	Nat vent + humidistat controlled extracts in wet rooms
Construction type	Timber frame
Occupancy	5 (unemployed)

Results	**what**	**value**
CO_2 (ppm)	**Annual mean**	1194.5
	Max. Monthly Mean	1400
	Min. Monthly Mean	1000
Relative humidity (%)	**Monthly mean**	58-68
Internal temperature (°C)	**Seasonal mean: Oct-Apr**	19.7
	Jul - Aug	23.8

Elm Tree Mews - Dwelling D

Dwelling type(s)	Mid-terrace
Floor area (m^2)	107
Standard achieved	
Air permeability (measured, $m^3/m^2/h$@50Pa)	6.75
Ventilation Strategy	Nat vent + humidistat controlled extracts in wet rooms
Construction type	Timber frame
Occupancy	3 (part-time employed) + 1 cat

Results	**what**	**value**
CO_2 (ppm)	**Annual mean**	643.8
	Max. Monthly Mean	800
	Min. Monthly Mean	500
Relative humidity (%)	**Monthly mean**	50-60
Internal temperature (°C)	**Seasonal mean: Oct-Apr**	-[7]
	Jul - Aug	21.1

[7] Monitoring not yet begun.

Elm Tree Mews - Dwelling E

Dwelling type(s)	Duplex flat
Floor area (m^2)	77
Standard achieved	
Air permeability (measured, $m^3/m^2/h$@50Pa)	6.17
Ventilation Strategy	Natural ventilation + humidistat controlled extracts in wet rooms
Construction type	Timber frame
Occupancy	1 (employed)

Results	**what**	**value**
CO_2 (ppm)	**Annual mean**	552.6
	Max. Monthly Mean	600
	Min. Monthly Mean	500
Relative humidity (%)	**Monthly mean**	45-55
Internal temperature (°C)	**Seasonal mean: Oct-Apr**	-[7]
	Jul - Aug	22.2

4.5 Glasgow House

Developer	Glasgow Housing Association
Dwelling type(s)	2 x 2.5-storey semi-detached 4 bed houses
Date complete	Sept 2010
Tenure	To be rented
Air permeability (measured, $m^3/m^2/hr@50Pa$)	1. 3 2. 3.2
Ventilation Strategy	MVHR
Control Strategy	
Heating System	Gas boiler
Floor area (m^2)	123

Monitoring

Method	where	how	when
CO_2	Kitchen, living room, all four bedrooms including one attic room and one single room.	Measured at 1-minute intervals using Eltek GD-47 transmitters recorded as a 5-minute mean value on an Eltek RX250AL1000 Series Squirrel Data Logger.	Initial study carried out in February 2011. The buildings are now forming part of an ongoing 2 year TSB performance evaluation study.
Relative humidity	As above but additionally in sunspace.		
Internal temperature	As above but additionally in sunspace.		

Experience

- Boost control was not straightforward to use; it was not clear when it was operating. This could lead to over-use or under-use.
- There was overheating in the first week of testing. In one house, the occupants therefore opened the windows. This will have had an impact on the indoor air quality.

Lessons for Future

- Specification and location of controls, including room thermostats and programmers, should be considered carefully.[1]
- The capacity of the ventilation system may need to be increased for high occupancy levels or to be sufficient for peak times.

Future developments

These two buildings were prototypes. Future Glasgow Housing Association developments will take learning from the research carried out here.

References

1. GLASGOW HOUSE Performance Evaluation Final Report – May 2011, Mackintosh Environmental Architecture Research Unit (MEARU)
2. Email conversation with Donald Shearer, Mackintosh Environmental Architecture Research Unit Glasgow School of Art, January 2012

Glasgow House – Dwelling 1

Dwelling type(s)	2.5 storey semi-detached, 4-bed
Air permeability (measured, $m^3/m^2/h@50Pa$)	3.0
Construction type	Clay block masonry
Occupancy	4 students for 2 weeks

Results	what	value
CO_2 (ppm)	Living room: Mean	598
	Max.	1909
	Min.	347
	Kitchen: Mean	977
	Max.	2552
	Min.	572
	Bedrooms: Mean	881
	Max.	2007
	Min.	478
Relative humidity (%)	External: Mean	86.5
	Living room: Mean	51.2
	Kitchen: Mean	49.2
	Bedrooms: Mean	43.3
	Sunspace: Mean	81.4
External temperature (°C)	Mean	5.5
Internal temperature (°C)	Living room: Mean	19.8
	Kitchen: Mean	20.7
	Bedrooms: Mean	20.0
	Sunspace: Mean	11.6

Glasgow House – Dwelling 2

Dwelling type(s)	2.5 storey semi-detached, 4-bed
Air permeability (measured, $m^3/m^2/h@50Pa$)	3.2
Construction type	Timber frame
Occupancy	4 students for 2 weeks

Results	**what**	**value**
CO_2 (ppm)	**Living room: Mean**	1019
	Max.	3301
	Min.	557
	Kitchen: Mean	1233
	Max.	3565
	Min.	693
	Bedrooms: Mean	937
	Max.	2097
	Min.	445
External Relative humidity (%)	**Mean**	81.0
Relative humidity (%)	**Living room: Mean**	43.4
	Kitchen: Mean	41.8
	Bedrooms: Mean	43.2
	Sunspace: Mean	69.8
External temperature (°C)	**Mean**	5.5
Internal temperature (°C)	**Living room: Mean**	21.3
	Kitchen: Mean	22.0
	Bedrooms: Mean	19.9
	Sunspace: Mean	10.6

4.6 Stamford Brook, Cheshire

Developer	Redrow
Dwelling type(s)	3 x 3 storey 3-bed end terrace; 1 x 2 storey 3-bed mid terrace
Standard achieved	EcoHomes Very Good
Air permeability (measured, $m^3/m^2/hr$ @50Pa)	4.5 (mean of 44 properties)
Ventilation Strategy	MEV - Ventaxia Multivent system
Construction Type	Masonry

Monitoring

Method	where	how	when
CO_2	Master bedroom.	Vaisala GWM25 CO2 sensor. 2000ppm limit.	4 monitored from Oct 2005 to Oct 2007 – see details given for each dwelling.
Relative humidity	5 in entrance hall, kitchen, living room, master bedroom and bathroom.	Eltek GC-10 Temp/RH Radio Transmitter.	ditto
Internal temperature	ditto	ditto	ditto

Experience

- Ventilation design and air quality were early considerations in the design process. The air permeability target of $5m^3/m^2/hr$@50Pa led to concerns regarding air quality and specification of mechanical ventilation throughout the development (10 x MVHR, the rest MEV). Ventilation system supplier had input as early as Jan 2002.
- Research design team involvement raised awareness of possible problems, and how to avoid them. For example: avoided reliance on occupant operation that might lead to them switching off ventilation, avoided cooker hood integration that might lead to clogged filters, and added extra noise attenuation to avoid noise causing customer dissatisfaction with the systems.
- The design was informed by the research teams prototype performance standard for ventilation and indoor air quality, which aimed to:
  - Require provision of adequate means of ventilation
  - Prevent over-ventilation under adverse weather conditions
  - Eliminate sources of air pollution from the indoor environment

Lessons for future

- Experience of partnering in action to resolve problems as they were identified.
- Occupant concerns about noise levels were reduced following remedial measures.
- Routing of the ductwork and positioning of fan unit was a secondary consideration, complicating ducting layouts and reducing flow rates.

References

1. Lessons from Stamford Brook Final report; Report 2 – design process
2. Phone conversation with Jonathan Moss, Redrow

Stamford Brook – House A

Dwelling type(s)	3 storey end terrace, 3 bed house
Floor area (m^2)	105
Occupancy	3
Testing period	Oct 2005 - April 2007

Results	**what**	**value**
CO_2 (ppm)	**Max. Monthly Mean**	1050
	Min. Monthly Mean	600
Relative humidity (%)	**Ext. Max.**	89
	Ext. Min	66
	Max.	55
	Min.	35
External temperature (°C)	**April Mean**	20
Internal temperature (°C)	**Living room: Max.**	26
	Min.	18

Stamford Brook – House B

Dwelling type(s)	2 storey mid-terrace, 3 bed house
Floor area (m^2)	84
Occupancy	2-3
Testing period	Nov 2005 - Nov 2006

Results	what	value
CO_2 (ppm)	**Max. Monthly Mean**	900
	Min. Monthly Mean	550
Relative humidity (%)	**Ext. Max.**	89
	Ext. Min	66
	Max.	60
	Min.	45
External temperature (°C)	**April Mean**	20
Internal temperature (°C)	**Living room: Max.**	25
	Min.	18

Stamford Brook – House C

Dwelling type(s)	3 storey end terrace, 3 bed house
Floor area (m^2)	105
Occupancy	2
Testing period	Nov 2005 - April 2007

Results	what	value
CO_2 (ppm)	Max. Monthly Mean	800
	Min. Monthly Mean	450
Relative humidity (%)	Ext. Max.	89
	Ext. Min	66
	Max.	60
	Min.	45
External temperature (°C)	April Mean	20
Internal temperature (°C)	Living room: Max.	25
	Min.	18

Stamford Brook – House K

Dwelling type(s)	3 storey end terrace, 3 bed house
Floor area (m^2)	129
Occupancy	2
Testing period	Nov 2005 - April 2007

Results	**what**	**value**
CO_2 (ppm)	**Max. Monthly Mean**	1000
	Min. Monthly Mean	500
Relative humidity (%)	**Ext. Max.**	89
	Ext. Min	66
	Max.	65
	Min.	50
External temperature (°C)	**April Mean**	20
Internal temperature (°C)	**Living room: Max.**	25
	Min.	17

4.7 The Wintles, Bishop's Castle, Shropshire

Developer	Living Villages
Dwelling type(s)	2 x houses
Date complete	2001
Tenure	private
Construction type	Timber frame
Heating System	LPG + wood stove

Monitoring details

Method	where	how	when
CO_2	Living room	Non dispersive infrared (NDIR) sensor (5000ppm).	6 min intervals over 7 days, less two 12-hour periods*
Relative humidity	Master bedroom, living room and garden, 1000-1500mm above floor level	Gemini TiniTalk datalogger sensors	6 min intervals over 7 days, less two 12-hour periods*
Internal temperature	Master bedroom, living room and garden, 1000-1500mm above floor level	Gemini TiniTalk datalogger sensors	6 min intervals over 7 days, less two 12-hour periods*

***Within in the sampling period, there were two 12-hour sessions where the ventilation was switched off or the passive ventilation inlets and outlets were sealed**

Occupant feedback

Method

Occupants were asked to rate their perception of the indoor air quality as 'Very good', 'Good', 'Satisfactory', 'Poor' or 'Very poor'.

Experience

- Dwellings 1 and 2 featured large open spaces across three storeys.
- Dwellings 1 and 2 were found to have ventilation systems that were over-ventilating.[2]
- Knowledgeable occupants altered the fan speed to suit their occupancy patterns.[2]
- The rural setting ensured external air quality was also high.
- Occupants reported their homes feeling ‘fresh’ from the start of their occupancy. This may have been because mostly natural products were used in the finishes.[2]
- Air permeability was relatively high for low energy homes. This may have affected the efficiency of the ventilation systems.[2]

Lessons for Future

- Detailing should be carefully considered in order to achieve better airtightness.
- Noise should be considered in siting the ventilation system
- Accommodation of ducting should be considered at an early stage

Future developments

Not known

References

1. Ian Mawditt, A Field Investigation of Indoor Air Quality and Ventilation in Low Energy Homes in England (MSc Thesis, 2006)
2. Questionnaire completed by Ian Mawditt, Four Walls, November 2011. Ian carried out performance testing of the dwellings.

The Wintles - Dwelling 1

(House 1)

Dwelling type(s)	4-bedroom, detached house
Floor area (m^2)	185.8
Air permeability (measured, $m^3/m^2/h$@50Pa)	6.88
Ventilation strategy	MVHR
Control strategy	Continuous automatic
Occupancy	3 + 1 dog

Results	what	value
CO_2 (ppm)	Ext.	390
	Mean	668
	Max.	931
	Min.	547
Relative humidity	Mean	47.5
	Max.	57.5
	Min.	32.9
Internal temperature (°C)	Bedroom: Mean	17.4
	Max.	21.6
	Min.	15.3
	Living room: Mean	18.2
	Max.	24.8
	Min.	14.2

Feedback

Occupant described the indoor air quality as ‘very good’.

The Wintles - Dwelling 2

(House 2)

Dwelling type(s)	3-bedroom, detached house
Floor area (m^2)	177.5
Air permeability (measured, $m^3/m^2/h$@50Pa)	7.95
Ventilation strategy	MVHR
Control strategy	Continuous medium speed
Occupancy	2 + 1 dog

Results	what	value
CO_2 (ppm)	Ext.	380
	Mean	732
	Max.	930
	Min.	590
Relative humidity (%)	Mean	41.1
	Max.	56.5
	Min.	32.9
Internal temperature (°C)	Bedroom: Mean	20.3
	Max.	25.2
	Min.	18.8
	Living room: Mean	21.1
	Max.	25.9
	Min.	19.1

Feedback

Occupant described the indoor air quality as ‘very good’.

The Wintles - Dwelling 3 (House 3)

(NB The IAQ in this dwelling is not 'good' and is presented for information only)

Dwelling type(s)	3-bedroom, semi-detached house
Floor area (m^2)	89.2
Air permeability (measured, $m^3/m^2/h$@50Pa)	4.64
Ventilation Strategy	PSV
Control strategy	Inlets sometimes closed
Occupancy	4

Results	what	value
CO_2 (ppm)	Ext.	385
	Mean	1163
	Max.	1438
	Min.	882
Relative humidity (%)	Mean	69.3
	Max.	90.7
	Min.	50.6
Internal temperature (°C)	Bedroom: Mean	20.3
	Max.	25.2
	Min.	18.8
	Living room: Mean	21.1
	Max.	25.9
	Min.	19.1

Feedback

Occupant described the indoor air quality as 'good'.

4.8 Other Experience

This section presents additional experiences of attempts to create good indoor air quality in low energy homes, which do not yet have quantitative evidence available. Despite a lack of data proving good indoor air quality, these anecdotes do provide experiences that are relevant to the discussion that follows.

Lincoln Close, Bladon, Oxfordshire

Built by private developers, Kingerlee Homes, the houses in Lincoln Close were constructed using masonry construction. During performance testing and monitoring, relative humidity was found to be at a high level. Beyond the first year of occupation, no problems with humidity have been noted. Further monitoring of the dwelling, to begin shortly, should confirm this with data.

The reason for the excess moisture is believed to be the long drying out period required for this type of construction combined with the high level of airtightness of the building envelope. In future, a longer drying out period will be factored into planning of the construction process.

Elm Tree Mews House B

In Dwelling 2 (House B), residents had closed most trickle vents and turned off fans in bathrooms and toilet, due to noise. The resulting air quality was poor. However they did not complain of feeling stuffy. Therefore this problem may not have been picked up without the monitoring.

Dartmouth Avenue, Woking, and Manor Farm, Guildford

Having considered the living conditions in standard new homes, these two developments were built by Greenoak Housing to provide better, more sustainable dwellings for their tenants. Their architecture makes them light and airy. Ventilation and services were considered from the outset.

Now occupied, the ventilation runs constantly, without automatic boosting operated by sensors. Occupier control is limited to a boost facility for the kitchen.

Residents in Dartmouth Avenue, provided with whole house MEV, have encountered no problems with ventilation. At Manor Farm, some issues occurred with the MVHR. One home was found to have the MVHR unit fitted the wrong way round when a resident reported high levels of condensation. This was despite a design and installation contract with the system’s manufacturers. Once rectified, all homes were believed to have improved ventilation and indoor air quality.

Surveys were carried out to establish resident perception of their homes. Overall resident satisfaction was very high. Occupants reported improvements in allergies to be satisfactory or better, including one commenting, 'the air seems fresher in here; my kids have less hayfever'.

Greenoak maintains the ventilation systems with cleaning twice a year. This means the location of the units is made readily accessible. Any problems with installation and commissioning are now avoided by using a consult, independent of the fitters, to check all installations on behalf of Greenoak.

Grosvenor Waterside

Dominion A2 provided anecdotal evidence at the GHA VIAQ WG meeting regarding Grosvenor Waterside - 20 properties were revisited following the installation of MVHR units. Twenty per cent of these were revealed to be lacking the access required for servicing. As a result of this experience, all of the properties will now be inspected and Ventaxia are providing extra free training for staff.

Filters that have been accessed were found not to need checks as often as every 3 months.

5 Good Practice

This investigation asked the question:

What lessons are emerging from monitored new low energy homes, regarding good ventilation performance and indoor air quality?

In order to answer this main question several sub questions were set:

- *What evidence is available, regarding the real performance of new low energy homes?*
- *What evidence is there of good indoor air quality and ventilation performance in new low energy homes – data and anecdotal?*
- *What evidence is there for how the design, construction, commissioning and operation have influenced the indoor air quality and ventilation performance?*
- *What further work is needed in order that this question might be answered more effectively?*

This investigation has revealed that there is still limited evidence for the real performance of low energy homes, and still less regarding good practice ventilation and indoor air quality. The TSB and GHA monitoring programmes have recruited a large number of projects committed to measuring real performance. However, due to delays, many of these projects have only recently started their monitoring programmes. A large amount of evidence is expected to emerge over the next two years, which will inform discussion around this topic further.

5.1 Identifying good practice from the evidence

Despite the limited number of examples that were able to provide evidence of good ventilation and indoor air quality, the sites presented here highlight some of the most significant issues.

Evidence of good indoor air quality from many of the examples presented in this report, indicates good practice, and is highlighted below. However some of the examples provide evidence of good indoor air quality that may not have resulted from deliberate good practice:

Feedback

Some monitored dwellings revealed evidence of poor indoor air quality or ventilation performance at an early stage. This offered the opportunity for the correction of installation errors or poor operation. Therefore good indoor air quality may have only been achieved as a result of the learning opportunity offered by the monitoring process itself. This stresses the importance of an effective quality assurance process. It also raises implications for the wider house building industry, where many new low-energy homes that are not monitored, may have undiagnosed ventilation and indoor air quality problems.

Short-term problems

The indoor air quality was initially poor at Bladon, causing condensation problems. However, this was a temporary problem relating to the extended drying out period needed for masonry construction of an airtight building. Additionally this experience has been used to inform further developments, which will be monitored.

Because commissioning often takes place before the building is finished, sanding and sweeping may take place with ventilation systems on. If the filters are not changed before occupation, the build up of dust on filters may erroneously indicating a need for more frequent changes than would be required under normal conditions. As most MVHR systems have time indicators, rather than air resistance indicators, this can set up a pattern of checks that might be more frequent than needed.

These examples illustrate that initial poor indoor air quality due to a short-term problem, may mask otherwise good practice.

Chance

Good indoor air quality in Elm Tree Mews appears to be accidental to a large extent. The passive ventilation strategy originally planned, was cut to save costs. The resulting ventilation measures may not have been sufficient to provide good indoor air quality. However, the original air permeability target of $3m^3/m^2/hr@50Pa$ was omitted from the specification, resulting is tested air permeability of between 6.2 and $8.6m^3/m^2/hr@50Pa$. The good indoor air quality, therefore, appears to result from the combination of a relatively leaky envelope, low occupancy and a large volume.

5.2 Achieving good indoor air quality

Ventilation and indoor air quality needs to be considered throughout the process of design and construction of the dwelling and beyond. The following highlights crucial aspects that need consideration at each stage, in order to provide good ventilation and indoor air quality in new low energy homes. In each case, good practice is described, and any examples providing evidence identified in brackets. (Some of this evidence relates to good practice, and some emerges from lessons learned.)

Design Stage

- The ventilation strategy must be considered from the start (Arun Crescent), involving designers, site managers, installation contractors, commissioning engineers, and supply chain etc. (Stamford Brook)

- The ventilation strategy should be designed together with the airtightness strategy, at an early stage. Implications of any changes to this must be considered. (Elm Tree Mews)
- Natural ventilation strategies such as passive stack will be dependent on the dwelling form, position, openings etc, and therefore may be compromised by changes to the design. (Elm Tree Mews)
- Mechanical ventilation systems should be designed to ensure that good air quality can be delivered to all areas of the home, and meet varying conditions, including increased occupancy. (Glasgow) This should of course, also apply to natural ventilation strategies.
- Passivhaus design is driven by good indoor air quality as well as reduced energy demand, but its application is still at an early stage in the UK, and dependent on skills availability. (Dunoon)
- Sufficient space for ducting must be accommodated within the design of the building. Layouts that are shorter and with fewer turns are preferable, and this should be considered with development of the layout and form of the building (Stamford Brook). Rigid ducting is less likely to buckle and block (Arun Crescent), and provides less resistance to flow. For extract systems, location of bathrooms and kitchen next to external walls or roof, allows more direct ducting.
- Avoid integration of the cooker hood into the extract system to reduce risks of clogging. (Stamford Brook)
- The location of access for maintenance should be considered carefully, particularly for mechanical systems requiring regular checks. Filter changes and cleaning may need to be undertaken frequently. For example, according to early experience many MVHR filters have been found to need cleaning once every 3 months. If the system is in the loft, it seems this is likely to be neglected because the unit is not likely to be readily accessible (Arun Crescent). The rooftop location of wind-cowls at BedZED means these have received no maintenance since completion.

Construction

- Actual as-built air permeability will be crucial to the ventilation performance, in terms of energy demand and air quality. A specific air permeability level targeted as part of a ventilation strategy must be met. The implications of achieving higher or lower levels in tests should be considered in the development of the ventilation strategy. (Elm Tree Mews)
- The type of construction should be considered, and the implications of an extended drying out period in masonry airtight homes. (Bladon)
- The construction process can produce large quantities of dust, which may take up to 6 months to settle, and can block filters and ducts in ventilation systems. (comment at GHA VIAQ working group meeting, Nov 2011)

Installation and commissioning

- The industry needs to be aware of issues arising due to the present immaturity of supply chains, and the lack of skills regarding the installation of new technologies. Where MVHR is concerned, this poses a particular problem for indoor air quality. But this is a wider issue impacting on other new technologies such as heat pumps, Solar Hot Water etc, which may also be installed in new low energy homes. Effective training for installers and an extra layer of quality assurance checking is needed in order to deliver performance to the level expected (Dunoon, Manor Farm). Additionally, the fragmented nature of installations makes it difficult to identify who has responsibility.
- Minor problems with installation may be easily fixed, but only if they are identified early on by thorough checks.
- Installation that allows easy access for maintenance is crucial (Grosvenor Waterside).

Occupancy and Operation

- Avoid noise from the ventilation system, which may lead the occupants to turn off or tamper with the system. (Stamford Brook).
- Avoid reliance on occupant operation, to reduce the risk of tampering (Stamford Brook). There are conflicting views on this issue. Occupants can be happier and more forgiving if they have control over their environment. However, if information and control is not clear and simple, the system performance can be undermined.
- Information and guidance for occupants regarding the operation of ventilation systems, that is clear and accessible, is crucial. Many of the examples here initially had problems due to occupant behaviour, and lack of awareness.
    - Following experience at Arun Crescent, the user manual for future Saxon Weald developments will include a DVD demonstrating the use of all systems for easy reference by the occupants.
    - Following experience at Dunoon, a simpler occupant user guide was requested from the manufacturer.
- Varying occupancy rates should be considered. In Glasgow House B measured CO_2 levels exceeding 3500ppm during one evening where 6 people were present.
- Occupant ratings for air quality should be viewed with caution, as perceived and measured air quality can differ significantly. Residents at the Glasgow houses may have a perception that the air quality is poor due to initial overheating. Occupants of House B at Elm Tree Mews rated their IAQ as good, despite inadequate ventilation and measured values that indicated that it was very poor.
- Overheating should be avoided in the heating season, as well as the summer. If occupants do not understand the heating system and open the windows to

reduce discomfort, the indoor air quality may improve, but heating energy will be wasted. (Glasgow House)

- Controls, including boost, should be simple, clear and accessible. (Glasgow House)
- Tools for process managing such as Soft Landings (BSRIA & UBT n.d.) can help to ensure that the operation of the building is informed and managed appropriately so that design intent is realised.

Maintenance

- A clear maintenance plan setting out who is responsible for maintaining any technology will help to ensure that the building performs as it was designed to. This plan should also be communicated to occupants so that they know who to go to when there's a problem.
- MVHR systems require regular cleaning and replacement of the filters to maintain performance. Only monitoring revealed that the advertised filter cleaning strategy was not sufficient at Arun Crescent. It was anticipated that filters would be checked and replaced once a year, along with the annual boiler check. Deterioration of the air quality and lowering of the ventilation rate were found after 3 months. Quarterly checks are now made on filters.
- However, this level of checking might not be appropriate at every property (A2 Dominion found quarterly was too often), and would need to be reviewed considering local particulates (TCH), construction dust and any other influences. This would indicate that filters should be replaced on or close to the day that a new owner takes possession.
- Different systems are accessed and cleaned in different ways and may pose different maintenance challenges. A system with incorporated filters will be more airtight, and therefore effective, but because of this, it will be harder to access and clean.

6 Conclusions and recommendations

6.1 Finding examples of good practice

Achieving good ventilation performance and indoor air quality is possible in low energy homes. However, because the measurement of real performance has only recently become established, very few properties are able to provide evidence of this. As a result, the conclusions here are limited, and further work is necessary.

6.2 Good practice

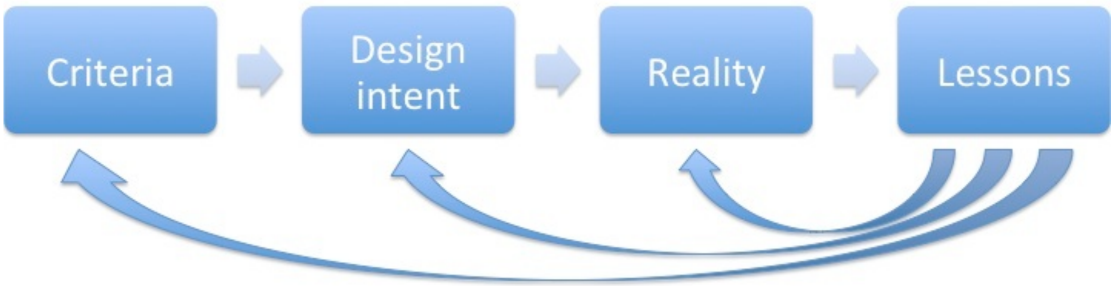
The evidence and stories presented here indicate that the ventilation strategy should be considered as a priority from the first stages of design. In some cases, it is described in contracts. The design of the building, the space and layout, all have an impact. The impact of any ventilation system needs to be taken into account throughout the design and construction process. Occupants need information and guidance on how and why their system should be used. Upkeep of the system is vital to maintain its performance.

6.3 Measurement methods

This report has presented results from a limited range of different studies measuring indoor air quality. It is evident that indoor air quality and ventilation is measured in only a small number of low energy buildings. For those that were found, methods for measuring differ significantly, and do not produce results that are comparable.

6.4 Feedback and learning

A major conclusion to emerge from this study relates to learning. If developers are interested in improving their buildings, monitoring that allows them to learn what in a building is working and what is not, can be immensely useful both in the short term and the long term. The lessons revealed by real buildings not only inform improvements to those buildings, but can influence the design intent in future buildings, and additionally can inform future regulation criteria.



Short term: Fine tuning

Initial problems with the way a building is operating can be corrected. These problems might be due to installation, maintenance or user awareness. However, design flaws are difficult to remedy at this late stage.

- Stamford Brook provided a good example of partnering in action, to resolve problems as they were identified.
- Occupant concerns at Elm Tree Mews regarding noise prompted remedial measures.
- Monitoring at Arun Crescent revealed lowering ventilation rates and poor IAQ that was identified as resulting from blocked filters.
- House B at Elm tree mews was revealed to have poor IAQ due to occupants turning off ventilation and closing trickle vents, and as a result this was remedied.

Long term: Changes to process

Experience from previous projects can inform better practice for future projects. As a result of the information revealed by monitoring, many of the developers mentioned here plan to improve their design, installation, and maintenance processes, and user information on future projects.

- Saxon Weald will use a DVD in user guide after experience at Arun Crescent.
- ZEDFactory have further developed the wind cowl system for further projects, following experience at BedZED.
- The research team at Dunoon will make recommendations to social housing providers regarding the importance of specification, installation, maintenance plans and occupant information.
- The research teams at Dunoon also make recommendations that the Passivhaus QA process should be tightened up regarding installation, due to the immaturity of the supply chain in the UK.
- Joseph Rowntree Housing Trust aim to use MVHR for future projects due to energy benefits, following experience at Elm Tree Mews.

A review of how effective each of these improvements proves to be would be a useful addition to the discussion here.

Many of the properties presented here have provided good results simply because they were monitored or studied. Problems with operation or installation were identified and rectified during the study process. GHA developer members and others have demonstrated their commitment to learning from experience in order to improve practice, and also to communicate these lessons to the wider industry.

6.5 The importance of feedback

It should be noted that the results of this study cannot be considered representative of mainstream house building. In developments where ventilation performance and indoor air quality has not been studied or checked, problems with commissioning and operation may not be identified or rectified. Additionally, the same mistakes may be repeated in future buildings.

With requirements for as-built performance likely to be included in future Building Regulations, the importance of achieving real performance that matches predictions, is becoming a mainstream issue. This is crucial in terms of ventilation and comfort performance as well as energy performance.

The Usable Building Trust states that:

> *buildings should be … safe, comfortable, convenient and healthy. People will soon notice if they are not … or if what they want to do is thwarted e.g. by poorly-functioning technology* (Usable Buildings Trust n.d.).

This highlights the importance of Building Performance Evaluation programmes such as Soft Landings, which help to incorporate feedback into the process. The house building industry would benefit from procedures ensuring that clear targets and strategies are planned from the start, performance checked, and information about a healthy internal environment gathered and used to inform future practice.

With future changes to Part L pushing towards lower carbon homes, improved airtightness and more mechanical ventilation are inevitable. Therefore the issues raised here are crucial for the creation of healthy low energy homes.

7 Limitations of this report and further work

7.1 Limitations

As detailed in previous sections, internal air quality is dependent on a number of variables, which have not been recorded in the dwellings presented in this study.

Pollution levels outside the dwelling and from internal sources will affect indoor air quality. The data sets we have considered do not include measurements of the emission rates and sources of pollution. Occupation rates and schedules, for example, would have provided valuable insights into ventilation performance. Where CO_2 levels meet our criteria, it might be that this is due to low occupation rates, rather than sufficiently high ventilation rates. The number of occupants were available for most of the examples, but were not backed up by information on timing of occupancy.

Consideration of **external conditions** was beyond the scope of this piece of work. However, the levels of moisture and CO_2 (as well as pollutants) and the microclimate will affect the conditions internally and, how and when pollutants enter the building. **Location**, **orientation** and **surface area of exposed walls** will also have bearing on solar gain and therefore the internal temperature and air pressure differences, and on the effect of winds on airflow, particularly through passive systems. A more thorough study of ventilation and indoor air quality would take into account these factors when judging the ventilation strategy.

Window opening affects the overall ventilation rate for any building. This behaviour has not been recorded for many of the examples, but would ideally be gathered in order to judge performance of the ventilation system and the envelope.

Limitations with the evidence presented here include the following:

- Data on CO_2^{in} has not been gathered, but CO_2^{out} has been inferred based on the mean CO_2 levels over time
- External temperature for comparison to internal temperature has not been gathered in all cases – this could indicate window opening behaviour. Detailed energy (as heating) usage might also indicate this.
- There is not a large enough sample for tests of statistical significance
- The limited amount of data available and the variability of the methods used to collect it, mean that direct comparisons cannot be drawn.

A qualitative analysis was made with the data found, not a quantitative analysis. Limited data from low energy dwellings was available when this research was undertaken. The exact method for taking measurements on the various sites varied, as did the data collected. We were, therefore, unable to make quantitative analysis across all of the dwellings for which data was available.

A largely immersive approach has been taken to this qualitative analysis, and therefore is limited by the views and experience of the authors. Theses limitations have been minimised as far as possible by inviting the views and input of those with expertise and experience in the field, through a series of working group meetings, email and telephone communications.

7.2 Further work, future work

This investigation has revealed several areas where further work is needed in order to further build an understanding of ventilation practice, and indoor air quality.

Beyond the scope of this investigation

- Carbon emissions resulting from electricity used by ventilation systems can outweigh heating energy carbon savings, in certain circumstances (Hestnes A G 1996). An investigation into electricity used by these systems under a variety of real conditions is needed to ensure that energy benefits modelled by SAP are realised in practice.
- Housing of different tenure will often have different occupancy patterns and management procedures, which will influence the most appropriate ventilation solutions. Without an effective maintenance plan, ventilation systems will not perform effectively. Work is needed to develop separate guidance for each situation.
- Detailed analysis is needed, of how effective present regulation is proving to be. It would be useful for work to be carried out, analysing what measures are being applied in new homes to comply with Part L and part F. And to evaluate which of these prove to be effective, and what further regulation measures are needed to ensure that new increasingly low energy homes are sufficiently ventilated.

Additional issues which are not directly relevant to indoor air quality, but which are influenced by many of the same variables:

- Overheating is emerging as a real risk in many new low energy homes. Work is needed to reveal the causes of this problem, and practical measures being applied to solve it.
- Interstitial condensation is raised as a serious problem, particularly in retrofit where internal insulation is applied and airtightness improved, without other measures.

Emerging evidence

One of the biggest challenges of this investigation was the lack of available data relating to real indoor air quality and ventilation performance. However, since improvements to airtightness driven by Part L and to ventilation provision set out in

Part F, more new homes are likely to meet the criteria of this study. Additionally, rising awareness of the benefits of post-construction testing and monitoring means that more developers will gather this type of data. Research results are expected to emerge, from projects funded by the Technology Strategy Board under their Building Evaluation Programme. The last of the funding tranche for this work closes on 23rd May 2012, therefore new evidence of best practice in ventilation should continue to be revealed over the next 2 years or so.

Defining 'good' indoor air quality

This investigation selected criteria from those set out in regulation and other documentation. These criteria related to carbon dioxide and relative humidity, two pollutants that served as indicators of air quality. However, measures of other pollutants were only taken in one of the studies used here. Research is needed into the real health implications of indoor air pollution, as well as influences on well-being and comfort. Research is also needed into identifying individuals most at risk from indoor air pollution, and those who might be exposed to poor ventilation conditions.

Measuring indoor air quality

This investigation found a variety of methods used for measuring indoor air quality. If benchmarks are sought, and comparisons made between different ventilation systems and buildings etc, then standardised methods for measuring need to be more clearly identified.

Perceived air quality seems to differ significantly from measured air quality, and perceptions tend to vary between individuals. Some of the most toxic pollutants are not detected by smell, so occupant evaluation will never be enough on its own. However, occupant discomfort may not always be identified by measurement. Research is needed that can evaluate occupant responses, and use these alongside measured values.

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Appendix A

Airtightness

Ventilation is provided through both uncontrolled means (leaky fabric), and controlled means (natural or mechanical). In order to control the heat lost through ventilation, it needs to be controlled as much as possible. Figure 8–A shows a chart presented in CIBSE Guide B illustrating the impact of air leakage on the ventilation rate of dwellings, against a target ventilation rate of 0.5-1ACH. An uncontrolled air leakage rate can vary significantly. This makes it difficult to:

- specify a final ventilation rate needed for good indoor air quality
- to predict ventilation heat loss, and heating energy demand.

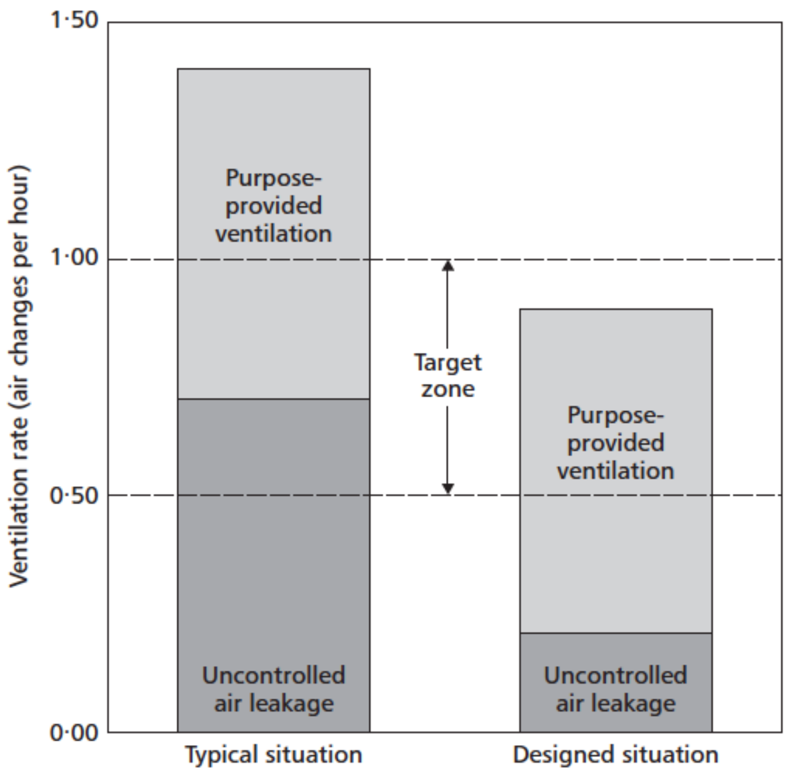

Figure 8–A Impact of air leakage on ventilation rate (CIBSE, 2005 Fig.2.8)

It can be seen here that if air leakage is greater than predicted, the resulting ventilation rate will be greater, causing ventilation heat loss and subsequent space heating demand to be higher than predicted. With increasing awareness of the importance of airtightness, it is also possible for dwellings to be built with lower air permeability rates than targeted. This situation can result in insufficient ventilation being provided to the dwelling, causing poor indoor air quality.

In order to deal with this issue, CIBSE Guide B states that: (CIBSE, 2005, p.2-28) *Target air leakage rates for domestic properties are:*

- *5 – 7 ACH at 50 Pa for dwellings having local extraction and background ventilation*
- *4 ACH at 50 Pa for dwellings having whole house ventilation systems.*

Building Regulations Part L sets regulations relating to the conservation of heat and power. This includes an approved airtightness level, in order to reduce uncontrolled ventilation heat loss. Approved Document L1A lists the worst acceptable standard of fabric air permeability as $10m^3/m^2/hr$@50Pa (ADL1A p.15, table 2). There are also requirements for pressure testing in order to demonstrate compliance. (ADL1A p.19).

As well as problems with predicted air leakage, the performance of purpose provided ventilation may also not meet design expectations. Problems can emerge with both natural and mechanical systems, due to poor design, installation, operation or maintenance. These too can lead to higher or lower than predicted ventilation rates, and influence delivered indoor air quality and energy savings.

Appendix B

Sources reviewed	Number of items reviewed
1. ZCH Matrix of literature on Ventilation and Internal Air Quality	145
2. A search of reports on low energy developments: • Responses to call for evidence in GHA newsletter • CLG Code Case studies 1, 2 & 3 • Low Carb 4 Real GHA Design Collection • Energy Saving Trust Case Studies • Building for Life Case Studies • HCA Case Studies • Passivhaus Conference proceedings 2006-2010 (only those papers presented in English) • Passivhaus Trust database of UK Passivhaus residential developments (database under development)	 2 13 4 6 8 4 233 34
3. GHA VIAQ Event presentations	10
4. Additional sources identified through sources 1 & 2, such as referenced articles, papers, reports etc.	2