The potential for energy saving in existing solid wall dwellings through mechanical ventilation and heat recovery

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Abstract

Mechanical ventilation with heat recovery (MVHR) is increasingly being promoted in the UK as a means of reducing the CO_2 emissions from dwellings and installers report growing activity in the retrofit market. The behaviour of a whole-house MVHR system installed in an experimental house, purpose built to typical 1930s standards, has been simulated, at a series of air permeability values corresponding to those achieved in the retrofit upgrading process. There is a critical value below which the air permeability, as measured in a 50 Pa pressurisation test, must fall before MVHR makes an overall energy saving. In the house considered this is 3–5 $m^3/m^2.h$ (4–6.5 ach^{-1}), although more significant savings of 9-12 % are achieved when the air tightness is improved to Passivhaus standards of 0.63 $m^3/m^2.h$ (0.6 ach^{-1}). When the CO_2 emissions are considered, the air permeability needs to approach Passivhaus standards to ensure an overall reduction, because the electricity needed to run the MVHR system has a CO_2 intensity almost three times that of the gas used to heat the house. Airtightness is a critical factor in achieving energy and CO_2 reductions and it is easy for designers to over-estimate the potential savings.

Introduction

In a typical unimproved UK solid wall dwelling the ventilation heat loss rate is approximately equal to the heat loss rate through the fabric (walls, roof and ground floor) so, in the context of Government targets of reducing CO_2 emissions from buildings, actions to reduce this heat loss are attractive. Building upon successful use in Passivhaus construction, mechanical ventilation with heat recovery (MVHR) is an established means of contributing to the achievement of the zero carbon homes standard required by UK legislation for all new homes by 2016. However, new homes will continue to be a small proportion of the total housing stock and it is necessary to take steps to improve existing dwellings as well. It is much more difficult to achieve low levels of air permeability by retrofitting an existing dwelling than when building a new one, and it is not clear to what extent users and specifiers of retrofit MVHR systems are aware of the importance of airtightness in achieving the anticipated savings. This paper reports work in progress, as part of a consortium research project to evaluate technologies for low-energy retrofit measures in solid wall dwellings, to attempt to understand the relationship between energy and CO_2 savings attributable to MVHR and whole-house airtightness.

Indoor air quality, ventilation and airtightness

Ventilation is needed to dilute and remove pollutants produced indoors, including moisture, body odours, cooking smells and VOCs, as well as to supply fresh outdoor air [1]. If moist air comes into contact with a cool surface, the relative humidity (RH) level increases, and when it exceeds 80 % the risk of mould growth increases rapidly [2]. Any surfaces below the dew-point temperature will permit condensation to form, a problem which is exacerbated if external constructions have poor thermal properties contributing to even lower surface temperatures. The development of damp, mould and fungi can result in degradation of occupant health and comfort, therefore it is important for the ventilation strategy to maintain RH levels

Table 1. International Comparison of Building Airtightness Standards.

Air Permeability Standards (tested at 50 Pa)				
UK(1)	Denmark	Finland(2)	Norway	Sweden(3)
10.0 $m^3/m^2.h$ (9.5 ach^{-1})(4)	2.5 $m^3/m^2.h$ (2.4 ach^{-1})(4)	1.0 $m^3/m^2.h$ (0.95 ach^{-1})(4)	2.5 $m^3/m^2.h$ (2.4 ach^{-1})(4)	2.2 $m^3/m^2.h$ (2.1 ach^{-1})(4)

1) Assumed value if built to accredited construction details
2) Guideline value, but must be tested if specified value is less than 4 $m^3/m^2.h$
3) Only a requirement when using elemental compliance method for dwellings with a floor area less than 100 m^2
4) Values converted from $m^3/m^2.h$ units to ach^{-1}, calculated using the geometry specific to the E.On 2016 house.

between 30–70 % [3]. This means that in general the ventilation rate needed to remove moisture is greater than that required to supply fresh air [4]. During the course of renovating an existing dwelling, it is important to consider the ventilation strategy when implementing measures to improve the building air tightness to ensure there is no detrimental effect on occupant comfort or the building fabric.

In the UK, the milder climate means dwellings predominantly rely on uncontrolled natural ventilation which does not guarantee a sufficient air change rate to maintain indoor air quality all year round, unlike MVHR, but on the other hand allows excessive ventilation and heat loss in windy conditions. Until the recent drive towards low carbon housing, the airtightness of UK dwellings showed little improvement. A survey of 471 dwellings reported by BRE in 1998 [5] indicated that the oldest properties tended to be the most airtight, with buildings constructed at the start of the 20th century having a mean air permeability only slightly exceeding 10 ach^{-1} at 50 Pa. Following a rise in permeability for houses constructed between 1930 and 1960, with the mean air leakage rate exceeding 15 ach^{-1} for the sample considered, the most recently constructed properties were achieving air tightness levels in line with those constructed at the start of the century.

Countries such as Denmark, Finland, Norway and Sweden experience colder winters compared to the UK. Dwellings there are constructed to considerably more stringent U-values (despite backstop U-values being less demanding in both Denmark and Finland compared to UK regulations) and better airtightness levels. Table 1 details the air permeability advised or required in each country for new construction. With the exception of the UK, the low air permeability values necessitate a method of controlled ventilation, and MVHR is installed as standard.

In terms of CO_2 emissions savings, the heat recovered from the controlled ventilation by MVHR offers an attractive potential contribution. As a result the market for MVHR systems in the UK has been stimulated and in 2009 was estimated at 15000 units annually, worth £30 million. Of this the retrofit sector accounts for a small but growing share of about 5 % [6]. Since the effectiveness of an MVHR system depends on the correct balance between heat recovery efficiency, fan efficiency, air flow rate and building airtightness there is a significant challenge in using MVHR in the retrofit sector in a market with no established tradition of its use. Do designers and specifiers realise the airtightness implications associated with using MVHR in existing dwellings or are occupants being led to expect unrealistic energy and CO_2 savings from installing systems in leaky dwellings?

PassivHaus standards [7] have been developed to enable the design and construction of dwellings with high levels of insulation and airtightness to keep the heating or cooling energy consumption below 15 kWh/yr/m^2 treated floor area. At this level, the ventilation system can address the space heating needs and a whole house MVHR system is an essential component of this strategy. For the MVHR to be effective it is recognised that the air leakage through gaps in the building fabric must be less than 0.6 air changes per hour at 50 Pa.

Although these standards strictly apply only to new builds, they are increasingly being implemented in refurbishment projects, and Octavia Housing have achieved the first certified Passivhaus retrofit in the UK for a terraced Victorian property [8]. However, the UK has a high proportion of hard to treat dwellings, typically with solid masonry walls [9], for which the typical energy saving measures are more difficult to apply. In these cases it is difficult to seal the fabric to such a high standard, and not always feasible to improve the U-values to Passivhaus standards. In addition to this, it is more difficult to accommodate the ducts needed for extraction of polluted air and supply of fresh air in an existing dwelling than in a new build, where false ceilings etc can be used and space designed in at the outset.

The 'hard to treat' nature of a significant proportion of UK dwellings means it will be a big challenge to meet the level or airtightness necessary to achieve energy and CO_2 emission reductions for the existing housing stock. However, with an anticipated 85 % of homes occupied in 2050 existing today [10] this is a problem which needs to be addressed.

Table 2 shows the recommended standards for flow rates, air tightness, and advised air tightness for MVHR, as defined by various bodies.

The CALEBRE project and the E.On 2016 house

CALEBRE (Consumer-Appealing Low Energy technologies for Building Retrofitting) is a consortium research project to establish refurbishment packages for reducing CO_2 emissions from dwellings, specifically targeted at solid-wall properties [11]. It is investigating heat pumps, vacuum double glazing, advanced surface treatments and insulation materials, as well as the MVHR systems that are the subject of this paper. The E.On House [12] considered in this investigation was newly constructed in 2008 on the campus of the University of Nottingham, but the property was built to 1930s standards so as to be representative of the 'hard to treat' housing stock. Featuring 3 bedrooms, the property has a total heated floor area of

Table 2. Building Airtightness Design Criteria.

Defining Body	Specified Building Air Tightness[5]	Advised Air Tightness for economic operation of MV system[5]	Advised MV Volume Flow Rate[5]
UK Building Regulations	**10.00 m^3/m^2.h at 50Pa** (9.54 ach^{-1} at 50Pa) (0.50 ach^{-1} background vent)	**5.00 m^3/m^2.h at 50Pa** (4.77 ach^{-1} at 50Pa) (0.24 ach^{-1} background vent)	**0.30 l/s.m^2** (0.36 ach^{-1}) (1.08 $m^3/h.m^2$)
Passivhaus	(0.63 m^3/m^2.h at 50Pa) **0.60 ach^{-1} at 50Pa** (0.03 ach^{-1} background vent)	**MVHR always necessary**	(0.28 l/s.m^2) (0.33 ach^{-1}) **1.00 $m^3/h.m^2$**
BRE Digest 398	Not specified	(4.19 m^3/m^2.h at 50Pa) (4.00 ach^{-1} at 50Pa) **0.20 ach^{-1} background vent**	(0.42 l/s.m^2) **0.50 ach^{-1}** (1.51 $m^3/h.m^2$) **All values reduced by level of background infiltration**

5) Value in bold indicates specified criteria whereas values in brackets indicate values converted to other units, calculated using geometry specific to the E.On 2016 house.

99.52 m^2. The house has been used to evaluate retrofit solutions comprising of suitable packages of intervention measures. The overall aim of the project is to be able to give validated advice to householders wishing to retrofit their solid wall dwelling. The work described in this paper contributes to this project.

Objectives

The objective of this investigation was to model the effect of installing an MVHR system on the heat losses, energy consumption and CO_2 emissions associated with the E.On 2016 house in the UK climate, at different stages of a retrofit process to reduce leakiness. Future investigations aim to establish the level of airtightness necessary for the system to be viable.

Methodology

An air permeability test using the 50 Pa fan pressurisation technique [13] was carried out on the E.On 2016 house (Figure **1**) in its initial state to establish the base case building air tightness. This was followed by the application of a series of retrofit solutions (refer to Table 3), installed over several months with the aim of reducing the level of uncontrolled ventilation. Air permeability tests were performed subsequent to the application of each measure to determine the effectiveness of improving the building air tightness.

This provided a series of measured permeability values which could be used to determine an infiltration value and input into a dynamic thermal model of the E.On house to calculate the impact on the building's annual energy consumption and CO_2 emissions. Some of the upgrades to the external fabric and glazing have multiple benefits in that they can contribute to reduced levels of infiltration in addition to reducing conduction losses. By measuring the changes in the building's air permeability it becomes possible to assess the combined effect of these improvements by updating these properties simultaneously in the thermal model which considers the series of retrofit measures which have been applied to the house.

DYNAMIC THERMAL MODELLING

Building geometry and location

Dynamic thermal modelling software (IES Virtual Environment) was used to build a model of the E.On 2016 house for the purpose of simulating a year's operation, and calculating the annual energy consumption and CO_2 emissions. Details of the building geometry and orientation were input using the architectural drawings to construct zones corresponding to each room in the house and form a representation of the building (Figure **2**). The Nottingham Test Reference Year (TRY) weather file was applied to simulate local climatic data.

Room templates

The operational parameters for each room type were derived from the NCM database [14] to develop a set of templates representing the occupied house, specifying heating set-points, domestic hot water consumption and internal gains (lighting, equipment and occupancy), as well as diversity profiles set-up to represent daily and weekly variations in these values.

These parameters were consistent for all the analyses undertaken so that the variations in energy performance would be solely related to the ventilation strategy and the thermal properties of the building constructions. The thermal modelling therefore assumes that there are no changes in the internal conditions before or after the application of the retrofit measures, and that the occupants do not take the benefit of higher living temperatures. Research into this 'rebound effect'[15] indicates that this aaumption is often incorrect, and as a result the measured energy performance associated with the operation of the property can vary significantly from the modelled results.

U-values

Construction templates were created defining both the internal and external construction build up, and performance characteristics. This allowed the changes in U-value between the initial base case house, as built to 1930s construction details, and the thermally upgraded construction, as per the improvement



Figure 1. E.On 2016 House, University of Nottingham.



Figure 2. IES VE Dynamic Thermal Model of E.On 2016 house.

work carried out as part of the retrofit process, to be replicated in the E.On 2016 dynamic thermal model. This would simulate the differences in conduction losses associated with the improved glazing and building fabric.

Infiltration

The airflow between the internal and external environment is complex in nature and subject to a number of parameters such as climatic conditions (e.g. wind pressure and speed) and the stack effect, and if the building is not airtight this can lead to a high level of infiltration which places an additional load on the boiler system.

The fan pressurisation technique (or 'blower door' test) applies steady state pressurisation/depressurisation in order to provide a quantitative assessment of the air leakage characteristics of the building envelope. The creation of a pressure difference across the building envelope means the airflow is forced, therefore the measured value does not represent the infiltration value under natural conditions.

Numerous studies have been carried out to investigate the correlation between the building air tightness and annual infiltration and Kronvall [16] derived a 'rule of thumb' method which divided the tested air change rate by 20. Dubrul [17] expanded on the rule to further account for the building exposure, suggesting a divisor of 10 for high rise exposed buildings and 30 for low rise, sheltered buildings. Both Sherman [18] and Jukisalo [19] developed calculation models which were considerably more detailed, taking into consideration factors such as climate zone, wind shielding, height of house, and size of cracks, with the latter even considering the distribution of openings across the building envelope. This however requires the collation of an extensive amount of data, for which some values are particularly difficult to establish and/or quantify.

For this study, it was decided to progress with Kronvall's simpler methodology of dividing the tested air change rate at 50 Pa by 20 to determine the infiltration level to apply for the modelling, after taking into consideration the height and exposure of the building.

INVESTIGATION OF THE E.ON 2016 HOUSE

Three studies were carried out to investigate the impact of the building air tightness on the calculated energy performance and CO_2 emissions for the building:

(i) Consideration of retrofit measures applied to the E.On 2016 house

- A series of retrofit measures have been applied to the E.On 2016 house over four stages, to study reductions in the building's energy consumption and associated carbon emissions. A pressure test was carried out after the implementation of each stage of improvement works, the results of which are recorded in Table 3.
- A series of simulations of the E.On house were carried out to model the series of improvements which have been undertaken on the property, as detailed above.
- The dynamic modelling was used to calculate the building energy consumption and CO_2 emissions associated with one year's operation of the building for the base case, and each successive stage of improvement measures.

(ii) Consideration of building air tightness with MVHR system of minimum building standard

- Operational requirements in the E.On 2016 house project forced the thermal upgrades and draught-proofing to be implemented simultaneously, which made it impossible to separate the two effects. Therefore the second study investigates the E.On 2016 house in its final, thermally upgraded, form and considers the effect of variations in the building air tightness. This work also extends the simulation to values of airtightness which have not yet been achieved by the package of measures so far applied to the house.

(iii) Consideration of building air tightness with MVHR system of best practice standard

- Building regulations provide minimum criteria to which services design must adhere, but it is possible to achieve further energy and CO_2 savings if the performance parameters associated with the system components are specified to best practice standards.
- The final investigation expands on the previous study by considering the effect on the building's energy performance and CO_2 emissions as a result of specifying best practice performance parameters for the MVHR system components (see Table 4). This analysis also extends the simulation to lower values of air permeability than have yet been achieved in the house.

Table 3. E.On 2016 house measured air permeability values.

Stage	Tested Air Permeability (at 50Pa)		Description of Work Carried Out
	($m^3/m^2.h$)	(ach^{-1})	
Base Case	15.57	14.85	Original State: • Single glazed windows • Uninsulated walls, floor and roof space • No draught-proofing
1	14.31	13.65	• Double glazing installed • Insulation applied to walls and loft • Draught-proofing applied to windows (excluding kitchen, bathroom and WC) and doors • Installation of whole house MVHR system
2	9.84	9.39	• Kitchen, bathroom, WC windows and under croft trap-door now draught-proofed • Draught-proofing throughout house re-done as inadequately installed • Window trickle vents blocked up
3	8.60	8.21	• Service risers sealed • Pipework envelope penetrations sealed (radiators, water pipes etc.) • Sealing around boiler flue • Covers fitted to door locks • Kitchen fan removed and bricked up
4	5	4.77	• Ground floor insulated and sealed

Table 4. Performance Parameters of system components.

Parameter	Minimum Building Standards [20]	UK Best Practice [21]
Specific Fan Power (Exhaust Only)	0.5 W/l/s	-
Specific Fan Power MVHR	1.5 W/l/s	1.0 W/l/s
Heat Recovery efficiency	70%	85%

Results

CONSIDERATION OF THE RETROFIT MEASURES APPLIED TO THE E.ON 2016 HOUSE

Each series of improvement measures applied to the E.On 2016 contributed to a reduction in the building's air permeability, but a large variation was observed in relation to the success of each stage (refer to Table 3).

The extensive stage 1 improvements were expected to yield a significant reduction in the measured air permeability but only succeeded in decreasing it by 1.26 $m^3/m^2.h$ (1.21 ach^{-1}). Inspection of the draught-proofing to the windows and doors revealed the work had been inadequately applied, often falling short of completing the seal around the perimeter of the fitting, and examination of the MVHR system revealed poor installation, creating newly exposed gaps in the building envelope and duct connections to the rooms, permitting airflow between the internal and external environment.

In stage 2 the draught-proofing was re-done and extended to the remaining doors and windows, which proved successful in achieving a more significant reduction of 4.47 $m^3/m^2.h$ (5.73 ach^{-1}), a considerable improvement on the previous attempt.

The building air permeability was further reduced by each of the remaining two stages, culminating in the final measure of sealing and insulating the ground floor which achieved the final building air permeability value of 5 $m^3/m^2.h$ (4.77 ach^{-1}) compared to the initial 15.57 $m^3/m^2.h$ (14.85 ach^{-1}).

Figure 3 details the breakdown of heat loss occurring due to external conduction, infiltration and ventilation at the moment when the peak space heating load occurs. Note that these peak loads do not occur on the same day of the year for each case.

A ventilation loss is introduced in stage 1 due to the installation of the MVHR system which supplies air to the rooms at just below the heating set-point, and therefore places a load on the space heating. The MVHR system is assumed to be running continuously. Between stages 1 and 3, the ventilation losses are

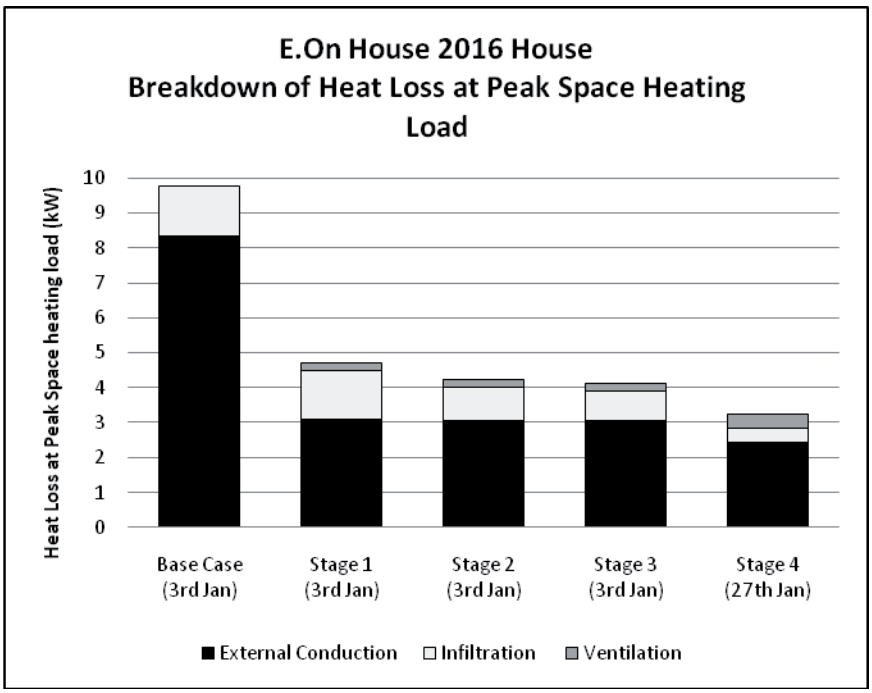


Figure 3. E.On 2016 House Breakdown of Heat Loss at Peak Space Heating Load.

Table 5. E.On 2016 house modelled annual energy consumption for retrofit improvements.

Stage	Annual Space Heating Energy (kWh/m^2)	Annual Auxiliary Energy (kWh/m^2)	Total Building Annual Energy Consumption (kWh/m^2)	Total Building Percentage Improvement over Base Case
Base Case	387.28	9.55	448.46	-
1	114.67	12.72	179.02	60.08%
2	99.16	12.72	163.51	63.54%
3	94.90	12.72	159.25	64.49%
4	65.40	12.72	129.74	71.07%

constant, but the improvements to the building's air tightness decrease infiltration and reduce the overall heat loss. Even after the Stage 4 improvements which reduce the building air tightness to $5m^3/m^2.h$ (4.77 ach^{-1}) at 50 Pa, the graph shows that the infiltration losses are still too high compared to the standards defined by Passivhaus. At this point the background infiltration accounts for 0.25 ach^{-1}, whereas the mechanical ventilation system is operating at 0.36 ach^{-1}, however the load on the heating system due to the controlled ventilation is marginally less as a result of the heat recovery.

The sealing and insulating work carried out to the ground floor in stage 4 contributes to a reduction in both the conduction losses and infiltration losses and as a result the peak space heating load occurs at a different time compared to the previous analyses. It should be noted that the ventilation system operates continuously, and that the associated losses will vary over the course of the day in relation to the temperature difference between the supply air and the room temperatures, which mean that the peak ventilation loss will not necessarily coincide with the peak space heating load, despite the ventilation rate being the same in all stages. As a result, the heat losses associated with stage 4 do not suggest an increase in ventilation losses, but indicate that the peak space heating load now occurs at a time where the ventilation losses are more significant.

Some of the characteristics displayed by Figure 3 are reflected by the values detailed in Table 5. A significant drop in the space heating energy is observed after the application of stage 1 measures due to the upgraded glazing and external constructions. The improved building air tightness contributes to further savings in stage 2 and 3, but the work on the ground floor in stage 4 achieves an overall 71 % improvement over the base case scenario for the total building energy consumption, which takes into account the energy associated with the space heating, domestic hot water, auxiliary (i.e. fans and pumps), lighting and equipment.

The base case scenario was installed with an intermittent extract system whereas the subsequent analyses featured a whole house MVHR system. Both ventilation strategies were modelled in line with the guidance specified in Approved Document F: Means of Ventilation [22] supplying 0.3 $l/s.m^2$ continuously throughout the year, equivalent to 0.3 W/m^2 or 2.63 kWh/m^2, assuming the best practice value from Table 4. This docu-

Table 6. E.On 2016 house modelled annual CO_2 emissions for retrofit improvements.

Stage	Annual Space Heating Carbon Emissions ($kg.CO_2/m^2$)	Annual Auxiliary Carbon Emissions ($kg.CO_2/m^2$)	Total Building Annual Carbon Emissions ($kg.CO_2/m^2$)	Total Building Percentage Improvement over Base Case
Base Case	76.68	4.94	108.31	-
1	22.71	6.57	55.97	48.32%
2	19.63	6.57	52.90	51.16%
3	18.79	6.57	52.06	51.94%
4	12.95	6.57	46.22	57.33%

ment [22] also states that an infiltration allowance can be applied to reduce the flow rate through the MVHR system, thus saving energy, if the building is leaky i.e. permeability >5m^3/m^2.h (4.77 ach^{-1}) at 50 Pa. Since the draught-proofing measures were an unknown variable prior to the fan pressurisation tests determining the building air permeability, the MVHR system in the E.On 2016 house has operated at the same volume flow rate throughout the retrofit process, without the application of the infiltration reduction.

At Passivhaus levels of air tightness of 0.63 m^3/m^2.h (0.60 ach^{-1}) at 50 Pa, the total air change rate due to controlled and uncontrolled ventilation equates to 0.36 ach^{-1} for the E.On house. At this air tightness, UK building regulations specify similar operational conditions, with a total air change rate of 0.39 ach^{-1}. However, specification of this fixed volume flow rate for mechanical supply, operating continuously and independent of the level of air tightness, means that the total air change rate due to controlled and uncontrolled ventilation increases as the building air tightness worsens, already exceeding BRE 398 guidance if it is allowed to deteriorate beyond 3 m^3/m^2.h (2.86 ach^{-1}) at 50 Pa.

Although not considered in the simulations undertaken for this paper, a control strategy which modifies the volume flow rate in response to operating conditions provides an opportunity to make further energy savings. Taking into consideration factors such as external temperature, as well as occupancy and relative humidity to control the level of flow rate, means that the fan does not need to operate at times when it is unnecessary, and this reduces the associated electricity consumption.

The MVHR system installed in the E.On house does not feature a control system which can modify the volume flow rate in response to sensed conditions: it has only a boost extract function. However, the specified volume flow rate for a 3 bedroom house as described by UK building regulations is the greater value of 21 l/s or 0.3 l/s.m^2. Based on this latter criterion the ventilation in the E.On house operates continuously at 30 l/s, which exceeds the advised 'boost extract' rate of 27 l/s, which would only be activated in order to control odours and relative humidity.

The CO_2 emissions corresponding to each stage of the retrofit measures are shown in At Passivhaus levels of air tightness of 0.63 m3/m2.h (0.60 ach^{-1}) at 50 Pa, the total air change rate due to controlled and uncontrolled ventilation equates to 0.36 ach^{-1} for the E.On house. At this air tightness, UK building regulations specify similar operational conditions, with a total air change rate of 0.39 ach^{-1}. However, specification of this fixed volume flow rate for mechanical supply, operating continuously and independent of the level of air tightness, means that the total air change rate due to controlled and uncontrolled ventilation increases as the building air tightness worsens, already exceeding BRE 398 guidance if it is allowed to deteriorate beyond 3 m3/m2.h (2.86 ach^{-1}) at 50 Pa.

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Table 6. The differences in the building performance compared to Table 5 relate to the space heating and equipment associated with the ventilation strategy. These are fuelled by different energy sources with different carbon intensities which mean that the overall reduction in CO_2 emissions is not as large as the reduction in the energy consumption. This will be discussed in more detail in the second study.

CONSIDERATION OF BUILDING AIR TIGHTNESS

It is difficult to differentiate the beneficial effects of the improved thermal properties from the reduced infiltration on the overall building performance, so this study takes the E.On 2016 house in its thermally improved state and investigates variations in the building's air tightness.

Beyond the building air tightness which has so far been achieved, an additional three analyses were carried out. While an air permeability of 5 m^3/m^2.h (4.77 ach^{-1}) is considered 'best practice' for refurbishment projects [23], an additional analysis considers an air permeability of 3 m^3/m^2.h (2.86 ach^{-1}), described as 'best practice' for new builds in the UK [4]. Two more analyses consider air permeability values at 1.05 $m^3/$

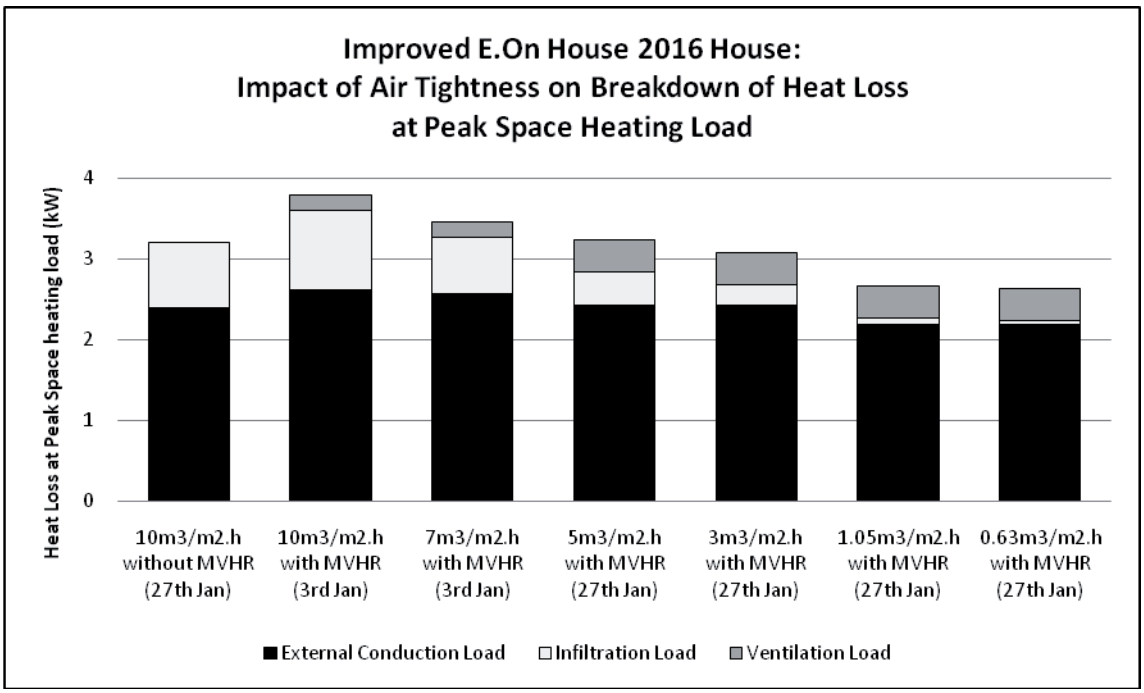


Figure 4. Impact of Air Tightness on Heat Loss at Peak Space Heating Load for upgraded E.On 2016 house.

m^2.h (1.0 ach^{-1}) and 0.63 m^3/m^2.h (0.6 ach^{-1}), the latter representing the standard set by Passivhaus.

An air permeability value of 10m^3/m^2.h (9.54 ach^{-1}) in the E.On 2016 house equates roughly to a background infiltration level of 0.5 ach^{-1} based on Kronvall's rule of thumb [16]. BRE digest 398 [24] advises a minimum air change rate of 0.5 ach^{-1}, therefore the E.On 2016 house at a 50 Pa air permeability of 10m^3/m^2.h (9.54 ach^{-1}), naturally ventilated with boost extract, has been taken as the initial case to which the subsequent analyses are compared. The impact of the whole house ventilation strategy is considered, and the building air tightness is progressively improved to establish whether this achieves a significant reduction in building energy consumption, and CO_2 emissions, compared to the initial naturally ventilated case. In this study, the infiltration allowance has been applied to the ventilation flow rate associated with the whole house MVHR to assess the potential benefits of this strategy.

Figure **4** details the breakdown of heat loss occurring due to external conduction, infiltration and ventilation on the date of peak space heating load for each stage of improvement and associated building air tightness. This assumes that the MVHR system components have been specified to minimum building standards.

The introduction of the whole house ventilation strategy to the very permeable house increases the overall heat loss because the introduction of the supply air increases the load placed on the space heating system. As the building air tightness is improved, the infiltration losses are reduced and the overall heat loss decreases. The ventilation load in the last column of Figure 4 is large compared to the infiltration load in column 1 (without MVHR) because this peak space heating load occurs when the heating system is switched on after the building has been unoccupied during the day. It takes a finite time for the extracted internal air to reach a temperature sufficiently above that of the supply air to allow heat to be recovered by the MVHR. As a result the ventilation losses appear higher.

When the 50 Pa air permeability drops to 5 m^3/m^2.h (4.77 ach^{-1}), the date of the peak space heating load changes and the ventilation losses form a greater proportion of the heat loss, but the overall value is similar to the initial naturally ventilated case. Further improvements to the building air tightness successfully reduce the overall heat losses to below the base case. It is worth noting that ventilation losses are related to the supply air which passes through the MVHR system, which indicates an opportunity to further reduce the heat losses if the heat recovery efficiency is specified beyond minimum standards.

As the air tightness is further improved to 5 m^3/m^2.h (4.77 ach^{-1}), the ventilation flow rate is increased because the infiltration allowance is removed, based on the guidance detailed in UK building regulations [24]. As a result there is only a marginal reduction in annual building energy consumption compared to the previous analysis at 7 m^3/m^2.h (6.68 ach^{-1}), because the savings in the space heating are negated by the increase in auxiliary energy associated with the higher flow rate.

Modelling the upgraded house with MVHR equipment specified to minimum building standards and an air tightness of 3 m^3/m^2.h (2.86 ach^{-1}) indicates success in achieving an overall reduction in annual building energy of almost 3 % when evaluated against the base case. This is increased to almost 9 % if the building air tightness is improved to Passivhaus standards of 0.63 m^3/m^2.h (0.6 ach^{-1}) at 50 Pa. The ventilation system will also ensure a reliable air change rate throughout the year, whereas this cannot be guaranteed by a natural ventilation strategy.

By comparison, when the MVHR system components are specified to best practice standards, the E.On 2016 house is able to achieve an overall reduction in building energy at an air per-

Table 7. Impact of air tightness on annual energy consumption for thermally upgraded E.On 2016 house.

Study	Annual Space Heating Energy (kWh/m^2)	Annual Auxiliary Energy (kWh/m^2)	Total Building Annual Energy Consumption (kWh/m^2)	Percentage Improvement in Total Building Annual Energy Consumption
10 m^3/m^2.h @50 Pa Naturally Ventilated	65.73	9.55	126.91	-
(ii) MVHR system specified to MINIMUM BUILDING STANDARDS				
10 m^3/m^2.h @50 Pa with MVHR[6]	78.51	11.83	141.97	-11.87%
7 m^3/m^2.h @50 Pa with MVHR[6]	68.38	11.83	131.83	-3.88%
5 m^3/m^2.h @50 Pa with MVHR[6]	65.40	12.72	129.74	-2.23%
3 m^3/m^2.h @50 Pa with MVHR[7]	58.84	12.72	123.18	2.94%
1.05 m^3/m^2.h @50 Pa with MVHR[7]	52.56	12.72	116.90	7.88%
0.63 m^3/m^2.h @50 Pa with MVHR[7]	51.23	12.72	115.57	8.93%
(iii) MVHR system specified to BEST PRACTICE STANDARDS				
10 m^3/m^2.h @50 Pa with MVHR[6]	76.36	10.81	138.80	-9.37%
7 m^3/m^2.h @50 Pa with MVHR[6]	66.34	10.81	128.77	-1.47%
5 m^3/m^2.h @50 Pa with MVHR[6]	62.89	11.40	125.92	0.78%
3 m^3/m^2.h @50 Pa with MVHR[7]	56.45	11.40	119.48	5.85%
1.05 m^3/m^2.h @50 Pa with MVHR[7]	50.30	11.40	113.33	10.70%
0.63 m^3/m^2.h @50 Pa with MVHR[7]	49.00	11.40	112.03	11.72%

6) Air change rate already achieved by E.On 2016 house in retrofit process

7) Anticipated future improvement to building airtightness

meability of 5 m^3/m^2.h (4.77 ach^{-1}). At 0.63 m^3/m^2.h (0.60 ach^{-1}), an 11.7 % reduction in annual building energy consumption is observed.

Table 7 details the modelled energy consumption calculated for the thermally upgraded E.On 2016 house at different levels of air tightness. The introduction of the whole house ventilation strategy specified to minimum building standards shows an increase in both space heating and auxiliary energy, resulting in an almost 12 % increase in total building energy, which also takes into account domestic hot water, lighting and equipment usage.

As the air tightness is further improved to 5 m^3/m^2.h (4.77 ach^{-1}), the ventilation flow rate is increased because the infiltration allowance is removed, based on the guidance detailed in UK building regulations [24]. As a result there is only a marginal reduction in annual building energy consumption compared to the previous analysis at 7 m^3/m^2.h (6.68 ach^{-1}), because the savings in the space heating are negated by the increase in auxiliary energy associated with the higher flow rate.

Modelling the upgraded house with MVHR equipment specified to minimum building standards and an air tightness of 3 m^3/m^2.h (2.86 ach^{-1}) indicates success in achieving an overall reduction in annual building energy of almost 3 % when evaluated against the base case. This is increased to almost 9 % if the building air tightness is improved to Passivhaus standards of 0.63 m^3/m^2.h (0.6 ach^{-1}) at 50 Pa. The ventilation system will also ensure a reliable air change rate throughout the year, whereas this cannot be guaranteed by a natural ventilation strategy.

By comparison, when the MVHR system components are specified to best practice standards, the E.On 2016 house is able to achieve an overall reduction in building energy at an air per-

Table 8. Impact of air tightness on annual CO_2 emissions for thermally upgraded E.On 2016 house.

Study	Annual Space Heating Carbon Emissions ($kg.CO_2/m^2$)	Annual Auxiliary Carbon Emissions ($kg.CO_2/m^2$)	Total Building Annual Carbon Emissions ($kg.CO_2/m^2$)	Percentage Improvement in Total Building Annual CO_2 Emissions
10 m^3/m^2.h @50 Pa Naturally Ventilated	13.01	4.64	44.64	-
(ii) MVHR system specified to MINIMUM BUILDING STANDARDS				
10 m^3/m^2.h @50 Pa with MVHR[6]	15.55	6.11	48.35	-8.31%
7 m^3/m^2.h @50 Pa with MVHR[6]	13.54	6.11	46.35	-3.81%
5 m^3/m^2.h @50 Pa with MVHR[6]	12.95	6.57	46.22	-3.52%
3 m^3/m^2.h @50 Pa with MVHR[7]	11.65	6.57	44.92	-0.61%
1.05 m^3/m^2.h @50 Pa with MVHR[7]	10.41	6.57	43.67	2.17%
0.63 m^3/m^2.h @50 Pa with MVHR[7]	10.14	6.57	43.41	2.76%
(iii) MVHR system specified to BEST PRACTICE STANDARDS				
10 m^3/m^2.h @50 Pa with MVHR[6]	15.12	5.59	47.40	-6.17%
7 m^3/m^2.h @50 Pa with MVHR[6]	13.13	5.59	45.42	-1.73%
5 m^3/m^2.h @50 Pa with MVHR[6]	12.45	5.90	45.04	-0.89%
3 m^3/m^2.h @50 Pa with MVHR[7]	11.18	5.90	43.76	1.97%
1.05 m^3/m^2.h @50 Pa with MVHR[7]	9.96	5.90	42.55	4.70%
0.63 m^3/m^2.h @50 Pa with MVHR[7]	9.70	5.90	42.29	5.27%

6) Air change rate already achieved by E.On 2016 house in retrofit process
7) Anticipated future improvement to building airtightness

meability of 5 m^3/m^2.h (4.77 ach^{-1}). At 0.63 m^3/m^2.h (0.60 ach^{-1}), an 11.7 % reduction in annual building energy consumption is observed.

Table 8 shows the percentage improvement in CO_2 emissions associated with improving the building air tightness. The reduction in the space heating is achieved by minimizing the ventilation losses and pre-heating the supply air using thermal energy from the exhaust. The impact of this is a reduction in gas consumption which fuels the central heating system: however in the UK the electricity used to power the operation of the MVHR system is almost three times more carbon intensive than gas. Consequently, at Passivhaus standards of airtightness, the building's annual CO_2 emissions achieve only a 2.8 % reduction for an MVHR system operating at minimum building standards compared to the naturally ventilated base case.

Table 8 also shows the percentage improvement in CO_2 emissions associated with an MVHR system specified to best practice standards. It can be seen that the values are slightly better as a result of the superior equipment parameters. As a result, the improved heat recovery and specific fan powers have reduced the carbon emissions such that, taking the different CO_2 intensity of the fuels into account, an overall reduction is achieved at an air permeability of 3.0 m^3/m^2.h (2.86 ach^{-1}), and a 5.3 % reduction is achieved at Passivhaus air permeability standards of 0.63 m^3/m^2.h (0.6 ach^{-1}).

Discussion

We believe that this is the first time such work in a UK setting has been reported, although there have been other studies relating to the use of MVHR systems in more extreme climates. The results of this modelling study will be of particular value to designers and specifiers, and highlight the importance of airtightness. However, there are some implications to be discussed as follows:

FUEL SOURCE

The carbon emissions reported in this paper are based on a building which operates under a gas powered heating system. This means it is more difficult to achieve a reduction in annual CO_2 emissions than in building energy consumption, as within the UK, gas is a less carbon intensive fuel source, at 0.198 kg. CO_2 per kWh, compared to the electrically operated MVHR system at 0.517 kg.CO_2 per kWh. The balance of these figures will be different in other countries with lower electricity carbon intensity.

In a property that features electric heating, the carbon intensity for both the space heating and auxiliary systems will be the same, therefore a reduction in CO_2 emissions can be realised as long as the decrease in space heating energy exceeds the electricity consumption associated with the MVHR unit. It should be noted however that space heating constitutes a considerable proportion of the total building energy, and if fuelled by electricity will result in a higher total building CO_2 emissions compared to the fuel strategy considered in this study. This means any reduction in space heating energy could be less significant when considering the overall building CO_2 emissions.

REBOUND EFFECT

The analyses assume that the information detailed by the room templates remain constant throughout the retrofit process, but it has been observed that occupant behaviour is subject to change after the application of the improvement measures [15]. This may be in the form of increased temperature setpoints in the rooms or differences in occupant activity, but these variations have an impact on the building energy consumption and mean that the anticipated savings predicted by the modelling may not be realised to the same extent in the actual E.On 2016 house. It is difficult to anticipate these changes prior to the application of the measures, therefore the modelled results are intended to be indicative of savings which could potentially be achieved. Future work will consider this in more detail.

IMPORTANCE OF LEGISLATION

Nordic countries have recognised the benefits associated with airtight buildings and have produced legislation stipulating minimum criteria. Within the UK, MVHR systems are gaining prominence, but there is a lack of appreciation of the importance of air tightness to ensure that overall energy savings are made. Building regulations need to set higher targets to ensure airtightness is being considered and addressed, and more focus needs to be placed on achieving these levels within the existing domestic stock.

The minimum standards often set the bar to which building services are designed, but current specifications cannot guarantee reduction in both building energy and carbon emissions. Improving these specifications to best practice standards can significantly improve the chances of reducing both parameters.

SIMPLIFICATION OF MODELLING

Dynamic thermal modelling is a time consuming process, requiring the collation, input and analysis of a large quantity of data. Since a number of scenarios were being considered in this instance a degree of simplification was applied to the modelling process which will have an impact on the results; for example the application of Kronvall's rule of thumb [16] to determine the infiltration level whereas the work of Sherman [18] and Jukisalo [19] uses a much more detailed process. This paper is a preliminary report of work in progress and future work will apply more detailed input data for selected scenarios, to provide a more extensive report of the building energy consumption and carbon emissions. That work will also investigate the extent to which these modelled savings are achieved in practice by considering the measurements of building performance being carried out in parallel with this study.

Conclusion

The modelling indicates a significant reduction in building energy and CO_2 emissions, achieving 71 % and 57 % respectively, through application of the retrofit solutions to the E.On house from its original base case state representing 1930's construction.

Based on the thermal upgrades which have been applied to the E.On 2016 house, and with MVHR equipment specified to minimum standards, the modelling shows that the air permeability must be reduced from the naturally ventilated base case of 10 $m^3/m^2.h$ (9.54 ach^{-1}) at least to 3 $m^3/m^2.h$ (2.86 ach^{-1}) to achieve a saving (3 %) in annual building energy, though further reduction to Passivhaus standards can contribute to a 9 % saving.

The carbon intensities associated with the electricity used to operate the MVHR system and the gas used for heating mean that, even at this low air permeability the CO_2 emissions are slightly increased. To achieve an overall reduction in the building's CO_2 emissions requires the space heating demand to be reduced by three times the electrical consumption associated with the operation of the ventilation system.

If the system components operate at best practice standards then the building demonstrates a reduction of 5.9 % and 2.0 % in annual building energy consumption and CO_2 emissions respectively, at an air permeability of 3 $m^3/m^2.h$ (2.86 ach^{-1}). At Passivhaus standards an 11.7 % and 5.3 % reduction in annual building energy consumption and CO_2 emissions is possible. We expect to be able to compare these modelled predictions with measured data in the near future.

The work confirms that airtightness is a crucial factor in achieving energy and CO_2 emissions reductions in dwellings and suggests that it would be easy to over-estimate the reductions achievable in typical UK dwellings.

References

1. Awbi, H. B. (2003). "Ventilation of buildings." London, Spon.
2. Roulet, C.-A. (2001). "Indoor environment quality in buildings and its impact on outdoor environment." Energy and Buildings 33(3): 183-191.
3. Carrer, P., M. Maroni, et al. (2001). "Allergens in indoor air: environmental assessment and health effects." The Science of The Total Environment 270(1-3): 33-42.
4. Energy Saving Trust (2005), "GPG224 Improving airtightness in dwellings." London, EST
5. Stephen, R.K. (1998). "Airtightness in UK Dwellings: BRE's Test Results and Their Significance." Report 359. UK, Building Research Establishment.
6. Waddell, B, personal communication, 21/10/10.
7. www.passivhaus.org.uk (accessed 3/3/11).
8. www.octaviahousing.org.uk (accessed 3/3/11).
9. Energy Saving Trust, February 2008. "A Study of Hard to Treat Homes using the English House Condition Survey." London, Defra.
10. CAG Consultants and Energy Action Scotland (2008), "Carbon Countdown for homes – How to make Scotland's existing homes low carbon." Perth, WWF Scotland
11. www.calebre.org.uk (accessed 3/3/11).
12. www.eon-uk.com/about/2016house.aspx (accessed 3/3/11).
13. Chartered Institute of Building Services Engineers (2000). "Testing buildings for air leakage." London, CIBSE.
14. www.2010ncm.bre.co.uk (accessed 3/3/11).
15. Sorrell, S. et al. (2009). "Empirical estimates of the direct rebound effect: A review." Energy Policy 37(4): 1356-1371.
16. Kronvall J. (1978) "Testing of houses for air leakage using a pressure method." ASHRAE Transactions 84(1):72-9.
17. Dubrul C. (1988). "Inhabitants behaviour with respect to ventilation." Technical note 23, UK: Air Infiltration Centre.
18. Sherman M. (1987). "Estimation of infiltration from leakage and climate indicators." Energy and Buildings 10(1): 81-6.
19. Jokisalo, J. et al. (2009). "Building leakage, infiltration, and energy performance analyses for Finnish detached houses." Building and Environment 44(2): 377-387.
20. Department for Communities and Local Government (2010). "Domestic Building Services Compliance Guide" London, NBS.
21. Energy Saving Trust (2006), "Energy efficient ventilation in dwellings – a guide for specifiers." London, EST
22. Department for Communities and Local Government (2010). "Approved Document F: Means of Ventilation." London, NBS.
23. Energy Saving Trust (2007), "CE83: Energy-efficient refurbishment of existing housing." London, EST
24. Building Research Establishment (1994). "Continuous mechanical ventilation in dwellings." BRE Digest 398. UK, BRE.