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Project CALEBRE

Consumer Appealing Low Energy technologies for Building RETrofitting

A summary of the project and its findings



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CALEBRE is an E.ON / Research Councils UK-funded research project involving a partnership of six leading UK universities, led by Loughborough University



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Foreword

Project CALEBRE (2008 – 2013) brought together the multi-disciplinary expertise of six leading UK universities to address some of the many challenges associated with the energy efficiency refurbishment of the UK's existing homes needed to help meet national carbon reduction targets.

From the outset, the approach was to put householders' perspectives and their lifestyles at the heart of our thinking around the technical developments and investigations that we undertook – and that could ultimately lead to refurbishment solutions that appeal to consumers. We principally focussed on challenges presented by 'hard to treat, hard to heat' properties – these are predominantly the 8.3 million solid wall houses making up 34% of UK housing stock, though many of our findings may be relevant to other house types.

We investigated a suite of selected techniques and technologies spanning the current, medium and longer term, informed by householder perspectives and supported where appropriate by business case modelling. The methods we employed have comprised laboratory investigations, field trials and modelling, together with user engagement techniques. Amongst the key outcomes generated by Project CALEBRE are the following:

- Knowledge of householders' attitudes to, and appetite for, refurbishment
- Establishing that the order of retrofit for common energy efficiency measures has an impact on energy and carbon reduction
- Factors related to achieving improved airtightness when refurbishing existing dwellings
- Technical improvements to gas and electric heat pump technologies, to allow ease of retrofit
- Advances to the emerging technology of vacuum glazing that reduce manufacturing costs
- Development of materials that could provide advanced surface treatments for the control of moisture and temperature
- Business case modelling to support mass manufacture of CALEBRE technologies (heat pumps and vacuum glazing)

The introduction of the Green Deal for promoting large-scale domestic energy efficiency refurbishment provides the perfect opportunity to launch the **CALEBRE Briefing Notes**, where key findings from the project are summarised. We offer these outcomes in a handy format to assist a growing refurbishment industry, to support current and future policy developments, and to help set further directions for research and development in the field of domestic energy demand reduction and refurbishment. We hope you find them useful.

Project CALEBRE has also generated many academic papers, and this is still on-going – some of these are referenced at the end of the Briefing Notes. We encourage you to look at these for fuller details of our work which takes its place alongside that of many others in contributing to the growing body of knowledge that can support UK Government and industry in achieving reduced energy demand by the UK housing stock. Going forward, we continue with further research on the workstreams that have been initiated. We also aim to bring to commercial success the technologies investigated, and seek to address wider questions related to building energy refurbishment. If you are interested in working with us, please contact us.

We thank many for their support – E.ON and RCUK for funding the project, and our Project Advisory Board (CIBSE, BRE, Edward Cullinan Architects, David Strong Consulting, academic colleagues from Aachen and Loughborough universities and University College London, and observers from E.ON and RCUK) for their advice and guidance throughout.

On behalf of the Project CALEBRE research team,

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March 2013

Index

The CALEBRE team Page 1

Project overview and summary of finding..... Page 2

Briefing Note 1 Airtightness improvements and ventilation systems in domestic refurbishment..... Page 4
 Authors: M Gillott, DL Loveday, K Vadodaria

Briefing Note 2 MVHR systems and airtightness improvements in domestic refurbishment..... Page 8
 Authors: PFG Banfill, SA Simpson, DL Loveday, K Vadodaria

Briefing Note 3 Impact of the order of domestic retrofit on long-term energy and carbon savings..... Page 11
 Authors: PFG Banfill, SA Simpson, DL Loveday, K Vadodaria

Briefing Note 4 Heat pumps for energy efficiency refurbishments of homes – reducing the hassle to householders..... Page 15
 Authors: RE Critoph, NJ Hewitt

Briefing Note 5 Energy efficiency refurbishments – householders’ appetite for improvement, and tolerance for change..... Page 18
 Authors: VJA Haines, V Mitchell, R Mallaband, DL Loveday, K Vadodaria

Briefing Note 6 Advanced technologies: Innovative materials for humidity control..... Page 21
 Authors: M Hall, E Tsang, S Casey

Briefing Note 7 Mapping occupancy and energy use in homes: An advanced real-time location and energy tracking system..... Page 25
 Authors: M Gillott, C Spataru

Briefing Note 8 Integrated system design and cost effective manufacturing solution for CALEBRE technologies for domestic for domestic refurbishment..... Page 29
 Authors: S Ratchev, K Agyapong-Kodua

Briefing Note 9 Vacuum Glazing..... Page 33
 Authors: PC Eames, T Hyde, F Arya, S Memon

List of outputs generated to date by Project CALEBRE..... Page 36

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Project overview

Project Overview and Summary of Findings

Project CALEBRE 'Consumer-Appealing Low Energy technologies for Building RETrofitting' (October 2008 – April 2013) was a £2 million E.ON / RCUK-funded research project comprising a partnership of six leading UK universities, and supported by a Project Advisory Board. Our aim was to contribute to addressing the challenge of reducing UK domestic energy demand and carbon emissions. With our focus largely on solid-wall, 'hard to heat, hard to treat' dwellings, we investigated a selection of current, medium and longer-term technologies for domestic energy efficiency refurbishment, with householder perspectives at the heart of our thinking. We approached this from a multi-disciplinary perspective, encompassing a range of techniques that included laboratory testing, simulation modelling, test house field trials and user engagement methods.

There are about 8.3 million solid wall properties in the UK, making up 34% of the housing stock and responsible for about 50% of all domestic carbon emissions. Refurbishment of these properties is necessary but challenging, and there are limited choices for reducing wall heat losses. Our scope therefore encompassed the following.

Other means to reduce heat demand:

- Airtightness and its improvement
- Mechanical ventilation with heat recovery (MVHR)
- Advanced window treatments – vacuum glazing
- Advanced surface treatments for moisture and temperature control

Efficient heat supply:

- Gas heat pump technology
- Electric heat pump technology

Householders and behaviour:

- Attitudes to refurbishment
- Retrofit practices
- Personal energy tracking
- Domestic thermal comfort

Detailed research findings have, and continue to be, disseminated through academic papers, conferences, presentations and the media – a list to date can be found at the end of this document. We encourage you to refer to these for full details and explanations. However, to assist the growing refurbishment industry, to help guide future policy, and to help plan future research directions, many of the key findings are summarised in the form of handy 'Briefing Notes' – we are delighted to offer these as a set in this booklet. Key outcomes from Project CALEBRE may be summarised as follows.

Householders' Attitudes to Refurbishment: For refurbishing older properties, barriers and opportunities have been identified relating to a number of aspects. As regards motivation, timing and cost, the need to repair and desire for comfort are key drivers, not energy demand reduction. Original house features are important to householders, with windows featuring highly amongst cherished items. When it comes to the refurbishment process itself, issues of trust of the professionals selected to carry out the work emerge as important. The project has uncovered some interesting attitudes to airtightness and ventilation which suggest that clear communication will be critical for conveying the benefits of a more airtight house, and of MVHR.

Householders' Behaviour – Orders of Retrofit: Using dynamic thermal modelling of a test house, sequences for retrofit of standard energy efficiency measures were investigated. It was found that the order in which retrofit measures are applied does matter, with the benefits and payback times of individual measures varying, depending on the preceding measures already installed. Clearly, this can impact upon refurbishment policies such as the UK's 'Green Deal' and its 'Golden Rule'. Early implementation of measures that achieve significant reductions in annual energy consumption and CO2 emissions, such as wall insulation and double glazing, are likely to yield the greatest cumulative savings.

Householders' Behaviour – Occupant Energy Tracking and Thermal Comfort: An innovative measuring technique deployed in Project CALEBRE was a real-time location and energy-tracking system. Installed in a test house, this enables the indoor locations of individual occupants to be tracked, together with their energy-consuming behaviours, thus permitting assignment of personal carbon footprints.

Whilst not intended for mass-deployment in homes, the technique provides a research tool for investigating domestic in-use occupant behaviour, and can quantitatively show how this might change in response to environmental conditions and refurbishment interventions. Project CALEBRE also undertook field investigations of householders' thermal comfort behaviour, and it is expected that a domestic thermal comfort prediction tool for UK dwellings will be available towards the end of 2013.

Airtightness and MVHR: Through practical test house trials, airtightness values achievable in a retrofit context have been measured. Whilst challenging, these levels of airtightness can be realised in practice through attention to detail during installation, and the findings highlight the need for quality of workmanship and the corresponding training that is required, together with confirmation by post-installation measurement. Dynamic thermal modelling of the test house has identified the levels of airtightness needed for MVHR to save energy and carbon, together with the need for proper installation and balancing.

Vacuum Glazing Technology: Essentially two or more sheets of glass separated by a vacuum, U values of 0.26 Wm⁻²K⁻¹ are achievable with triple vacuum glazing. Slimmer than standard double glazing, vacuum glazing can improve the performance of solid wall, and other, building envelopes. The CALEBRE project has brought this technology a step closer commercially via the development of new, lower-cost edge seals. Steps necessary for the long term maintenance of vacuum have been identified.

Advanced Surface Materials: Silica-based materials have been engineered for rapid response humidity and temperature buffering. These materials provide moisture absorption properties that are two orders of magnitude better than those currently possible with traditional interior building surface materials. The new materials are currently very expensive, and research is needed to support relatively inexpensive bulk manufacture. However, the new materials offer the potential to control indoor moisture using relatively small surface area treatments for building interior surfaces and thus help minimise potential unintended consequences related to refurbishment and moisture.

Heat Pump Technologies: Heat pumps are seen by many as key components of the future energy retrofit of UK homes, so it is essential that they are matched for integration with existing domestic systems. This means that they must offer the householder ease of retrofit, act as simple replacements for an existing boiler, and be capable of operating with the existing radiator network (output at 60oC) whilst still giving good performance. New technologies have been developed in Project CALEBRE to support these requirements. A thermal compressor has been developed and tested for gas-fired heat pumps to achieve 30% annual fuel savings compared with a condensing boiler, and yield a payback time of less than three years. It is planned as a split system, thus saving on garden space, and its commercial development is continuing via a spin-out company 'Sorption Energy'.

Economised vapour injection (EVI) and compressor-expander (CE) technologies have been developed for electric heat pumps, allowing operation at high temperature for direct retrofit. EVI is a viable product, competitive with cascade units. In laboratory tests, the CE unit gave a COP (heating) of 4.31, but needs further development. Energy storage is required to manage tariffs and electrical demand.

Business Models for Manufacture: Within the project, a systems design and manufacturing methodology has been defined. This has been applied to the design and manufacture of three CALEBRE technologies - gas heat pumps, electric heat pumps, and vacuum glazing – and the requirement specifications for large-scale production have been identified.

In closing, we trust that many in Government, industry and academia will find the outcomes from Project CALEBRE to be useful and informative. This year, the UK Government launched the 'Green Deal' to facilitate large-scale energy efficiency refurbishment of the UK housing stock. The project outcomes are therefore timely, and take their place alongside the work of many others, in contributing towards the achievement of the UK's 2050 carbon emissions reduction target.

Airtightness improvements and ventilation systems in domestic refurbishment

Authors: M Gillott, DL Loveday and K Vadodaria

Findings from Project CALEBRE BRIEFING NOTE NO. 1

Key messages and findings

Improving airtightness can help save energy, cut costs and reduce carbon emissions associated with the heating of our homes. Mechanical ventilation with heat recovery (MVHR) systems are increasingly being used in domestic refurbishment, not only to maintain adequate indoor air quality, but also to save energy in homes that are sufficiently airtight. When a house is being refurbished for energy efficiency, it is possible to achieve high levels of airtightness through attention to detail and quality of workmanship. As a result, optimum energy-saving performance can be achieved from properly-installed and balanced MVHR systems.

Context

Existing homes in the UK have varying levels of airtightness, ranging from 2 to 29 m³/(h.m²) @ 50Pa, with the least airtight dwellings being over 10 times as leaky as the most airtight dwellings (Stephen, 2000). Improving airtightness of existing dwellings is important, as leakage of warm air is a significant source of heat loss from our homes. It is even more important when considering energy savings achieved with the use of MVHR systems (see CALEBRE Briefing note No. 2). MVHR systems recover heat from air extracted from kitchens and bathrooms and use it to pre-heat the incoming fresh air supply to the house.

But, just how easy or challenging is it to achieve good airtightness when refurbishing a house?

In order to investigate this, the CALEBRE research project applied a range of refurbishment measures to a test house and evaluated the improvements achieved in airtightness levels.

What we did

The E.ON Retrofit Test House (Figure 1), built as a replica of a 1930s semi-detached dwelling, was used for this investigation. This house, in its base (as built) case, corresponds to how a house might be found if completely unrefurbished, and gave a measured airtightness value of 15.57 m³/(h.m²) @ 50Pa. The airtightness test was conducted using the blower door technique and was carried out to industry standard (all flues, chimneys and vents sealed during the tests, leaving only the unwanted leakage routes).



Figure 1: The E.ON Retrofit Test House

Through five successive stages of airtightness refurbishment, an airtightness value of 4.74 m³/(h.m²) @ 50Pa was achieved firstly through the application of the more conventional measures, and then by the adoption of more advanced measures. These are described in Table 1. Note that an MVHR system was installed at Stage 1, which may have increased air leakage due to fabric penetrations. Wall and loft insulation was also added at Stage 1, which may have reduced air leakage. Data presented should thus be taken as indicative, rather than definitive.

What we observed

Each set of applied retrofit measures contributed to an improvement in airtightness (lower values for air leakage), but with variable success (see Table 1). The extensive Stage 1 improvements were expected to significantly reduce air leakage, but succeeded in reducing it from 15.57 to only 14.31 m³/(h.m²) @ 50 Pa. Inspection revealed that the draught-proofing had been poorly applied to the windows and doors by the contractor, often with an incomplete seal around the perimeter of the component, and with gaps left around doors (Figures 2a and 2b).

At Stage 2, and following feedback by the research team, the Stage 1 draught-proofing measures were re-done by the contractor, together with the application of additional measures. This resulted in an airtightness value of 9.84 m³/(h.m²) @50Pa.



Figure 2a & 2b: Door and window perimeter seals: (a) as installed by contractor with gaps & (b) reinstalled with continuous seal

At Stage 3, further – more detailed – measures were applied. For example, sealing pipework penetrations (Figure 3). The kitchen fan was also removed and its opening bricked up (but see *** in Table 1). This latter measure was carried out because an MVHR system had already been installed and was in operation to extract air from the kitchen. At this stage, an airtightness value of 8.60 m³/(h.m²) @50Pa was recorded.

STAGE OF IMPROVEMENT	AIRTIGHTNESS ACHIEVED (m ³ /(h.m ²) @50Pa)	MEASURES TAKEN
Base case (as built)	15.57	Single glazed windows, uninsulated walls, floor and roof space, no draught proofing
Stage 1	14.31	Double glazing, draught-proofing applied to windows (excluding kitchen, bathroom and WC, due to current Building Regulations) and doors Additional work: installation of a whole house MVHR system*, insulation applied to wall cavity and loft**
Stage 2	9.84	Stage 1 draught-proofing re-applied (addressing inadequate installation) and including kitchen, bathroom and WC windows done 'at risk'***. Undercroft trap-door draught-proofed
Stage 3	8.60	Window trickle vents blocked up, service risers sealed, pipework envelope penetrations sealed (radiators, water pipes, etc), sealing around boiler flue wall penetration, covers fitted to door locks, kitchen fan*** removed and bricked up
Stage 4	5.00	Airtight vapour-permeable membrane installed over timber suspended floors (ground and first)
Stage 5	4.74	Taping wall / ceiling joint and covered with coving, plus minor snagging

* The MVHR system may have actually increased infiltration due to fabric penetrations

** This work was done at the same time and may have reduced infiltration

*** Applying air-tightness measures to kitchens, bathrooms and WCs could breach current Building Regulations due to presence of combustion appliances (eg. boiler, gas cooker), and was tried here for experimental purposes only. In practice, it is essential that combustion appliances always receive adequate ventilation.

Table 1: Measured airtightness values for staged improvements



Figure 3: Typical leakage paths in existing homes pipe penetrations

Stage 4 of airtightness improvement involved lifting floor coverings and furniture to install a vapour-permeable membrane over the suspended timber floor plus sealing at skirting boards. This procedure was carried out room by room and, in practice, the process was not dissimilar to fitting a new carpet. The vapour permeable airtightness membrane used has a current list price of £2.50 per m², which equates to a material cost of approximately £200 for a house with an internal floor area of 80m². This process may appear unconventional, but it achieved a significant improvement in airtightness, namely a value of 5.00 m³/(h.m²) @50Pa.

Further improvement in airtightness to a value of 4.74 m³/(h.m²) @50Pa was achieved at Stage 5 by taping the wall / ceiling joint and covering with coving, plus minor snagging.

The MVHR system was installed by a contractor (not the manufacturer) during Stage 1. Measured data indicated that the air supply rate was 20% in excess of its design value, and exceeded the extract rate. This imbalance led to over-pressurisation of the test house, leading to increased ventilation losses. Based on feedback by the research team, the MVHR manufacturer re-designed the controller for their products in order to allow independent fan speeds for better system balancing (Figure 4).



Figure 4: New controls to allow independent fan speeds for better system balancing supplied by the MVHR manufacturer

The installation of the MVHR system had created new gaps in the building envelope and at duct connections to the rooms, permitting uncontrolled airflow and increasing the air leakage. Infrared thermography revealed that previously installed loft insulation was left disturbed after the installation of MVHR ductwork, leading to heat losses (Figure 5). Infrared thermography also revealed that bends in MVHR ducts were simply taped without any insulation (Figure 6). In response to research team feedback, the MVHR installer re-insulated the ductwork to reduce heat loss.

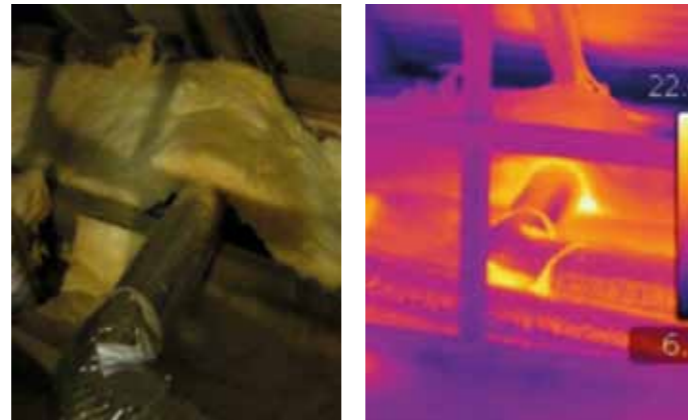


Figure 5: Loft insulation left disturbed after installation of the MVHR system by the contractor

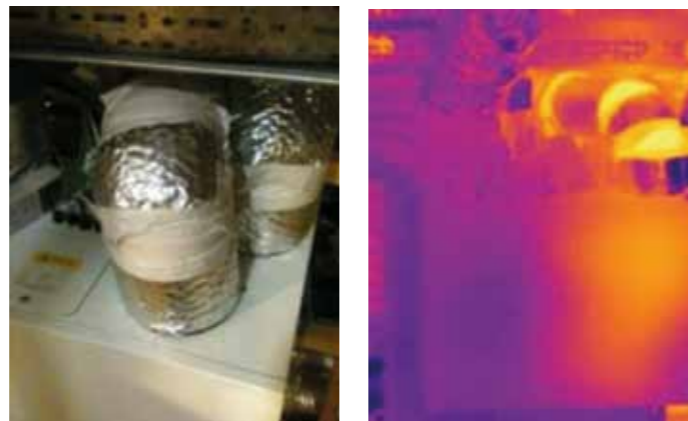


Figure 6: Bends of MVHR ducts were simply taped and left uninsulated by the MVHR contractor

Conclusions

The work has revealed that although improving the airtightness of a house is perceived as a relatively simple task, it is in fact much more challenging because of the care and attention to detail required by a workforce. Any installer would find it challenging to achieve low permeability by retrofitting. The data presented in this briefing note suggests that by combining readily available materials with the careful application of techniques and attention to detail, significant improvements in airtightness can be achieved in a refurbishment context for existing homes. There are, however, certain limitations that include properties with hard flooring, as well as the presence of open fireplaces. All combustion appliances must always be adequately ventilated.

The use of a vapour permeable membrane to seal the floor, and sealing at skirting boards (as described in Stage 4), can provide significant improvement in airtightness. There is scope for this to be developed as a standard procedure, perhaps in conjunction with carpet-fitting practices. However, the approach may not be suitable for properties with solid / hard flooring. Potential effects arising from reduced ventilation of timber floors should also be considered and investigated before widespread adoption of this technique.

Infrared thermography has further highlighted the need for attention to detail and quality of workmanship for effective energy refurbishment of existing homes. Better training of refurbishers will help. The modification to control systems by the MVHR manufacturer, insulation improvement works to the MVHR ducting by the installer, and improvement to draught treatments highlight the role research can play in working with stakeholders to identify problems, improve products, and inform refurbishment processes, leading to future best-practice standards for a refurbishment industry.

Recommendations

1. Attention to detail and quality control should be exercised when carrying out airtightness improvements and installing MVHR systems.
2. Adequate training should be provided to installers.
3. When carrying out airtightness improvements to properties, care should be taken to ensure an appropriate air supply to combustion appliances.
4. Some treatments may not be suitable for all properties – floor sealing, for example. The effects of reduced ventilation to timber floors should be investigated prior to widespread adoption.
5. High levels of airtightness can potentially affect indoor air quality. Correctly-installed MVHR systems can maintain or improve indoor air quality, and, at sufficiently-high levels of airtightness, also save energy.

References / Further reading

Standard Assessment Procedure 2005 – Appendix Q MVHR Installation Guide

Installation Guide and Checklist
Mechanical Ventilation with Heat Recovery
(Version – 11 February 2011)

The Electric Heating and Ventilation Association have developed this guidance and checklist document in partnership with the Residential Ventilation Association (a HEVAC association), BRE and EST.

Stephen, R. K. (2000) Airtightness in UK Dwellings. BRE Information Paper IP 1/00. Garston, Watford, Building Research Establishment

Banfill, P.F.G., et al. (2011) Mechanical ventilation and heat recovery for low carbon retrofitting in dwellings, *Proceedings of the World Renewable Energy Congress 2011*, Linköping, Sweden

Banfill, P.F.G., et al. (2011) The potential for energy saving in existing solid wall dwellings through mechanical ventilation and heat recovery, *Proceedings of ECEEE 2011 Summer Study on energy efficiency*, France

MVHR systems and airtightness improvements in domestic refurbishment

Authors: PFG Banfill, SA Simpson, DL Loveday and K Vadodaria

Findings from the CALEBRE Project BRIEFING NOTE NO. 2

Key messages and findings

Airtightness of existing homes needs to be improved when installing mechanical ventilation with heat recovery (MVHR) systems in order to maximise energy savings and carbon emissions reduction. Retrofitted MVHR systems should reach higher performance standards, where it can be challenging to achieve the low air permeabilities for existing dwellings, compared to new build. The quality of workmanship is critical to ensuring the optimal performance and achieving energy and CO₂ emission reductions.

Context

MVHR systems recover heat from the air extracted from kitchens and bathrooms and use it to pre-heat the incoming fresh air to a house. The market for MVHR systems in the UK was estimated at 15,000 units annually in 2009, worth £30 million. Of this market, the retrofit sector accounts for a small but growing share of about 5%. 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 technical challenge in using MVHR for retrofit. Achieving low air permeability values for existing dwellings adds to this challenge – it can be difficult to access and address sources of leakage (eg. service penetrations located behind fixed installations or constructions). As there was no prior information on this, the CALEBRE research project conducted an investigation to establish the airtightness level that must be achieved in order for MVHR to significantly reduce CO₂ emissions from existing dwellings.

What we did

The E.ON Retrofit Test House (Figure 1) – built as a replica of a 1930s semi-detached dwelling – was used as a case study to investigate the extent to which an MVHR system, fitted as part of an overall retrofitted strategy, would deliver energy savings and CO₂ emission reductions. The house was simulated, using dynamic thermal modelling (DTM) software, at six levels of airtightness (expressed as air permeability, as would be measured in a blower door test): 10, 7, 5, 3, 1 and 0.63 m³/(h.m²) @50Pa.

Existing dwellings may demonstrate higher air permeability values. However, it is believed that an air permeability of

10 m³/(h.m²) @ 50Pa can be achieved by basic draught-proofing measures, and corresponds with the minimum building standards for new dwellings. The lowest value (0.63 m³/(h.m²) @ 50Pa) corresponds to the Passivhaus standard of 0.6 ach⁻¹ @50Pa after conversion of units. The mid-range value, 5 m³/(h.m²) @50Pa, represents the measured air permeability achieved by the E.ON Retrofit Test House subject to extensive draught-proofing work (see CALEBRE Briefing note No. 1).



Figure 1: The E.ON Retrofit Test House which is being used to trial CALEBRE technologies

For each level of airtightness, two MVHR systems were simulated, representing systems specified to Minimum Building Standards (with a specific fan power of 1.5 W/l/s and heat recovery efficiency of 70%) and Best Practice Standards (with a specific fan power of 1 W/l/s and heat recovery efficiency of 85%). The annual energy consumption and CO₂ emissions were calculated and compared to the simulated naturally ventilated E.ON Retrofit Test House (ie. kitchen and bathroom extract fans but without MVHR) at an air permeability of 10m³/(h.m²) @50Pa.

What we observed

Installing an MVHR system in a “leaky” dwelling increases the building’s energy requirements because the MVHR system increases the air change rate. The extra air needs to be heated to maintain the internal temperature – although this will be partially offset by the heat recovery. Figure 2 shows this increased energy requirement for the E.ON Retrofit Test House (relative to natural ventilation) at air permeabilities of 10 and 7 m³/(h.m²) @ 50 Pa.

With an MVHR system specified to Minimum Building Standards it is necessary to improve the airtightness to 3 m³/(h.m²) @ 50 Pa. At this level of airtightness, the reduction in space heating energy exceeds the energy expenditure required to operate the MVHR system.

The MVHR system uses electricity to operate, which is more carbon intensive than the mains gas used for the space heating system. This means that a greater reduction in space heating energy is needed to offset the increased electricity consumption and ensure an overall reduction in CO₂ emissions. Figure 3 shows that an air permeability of 1 m³/(h.m²) @ 50Pa is needed for an MVHR system specified to Minimum Building Standards to achieve an overall reduction in CO₂ emissions.

An MVHR system operating to Best Practice Standards achieves energy savings and CO₂ emission reductions at an air permeability of 5 and 3 m³/(h.m²) @ 50Pa, respectively. These air permeability values are less onerous than those for the Minimum Building Standards performance specifications. MVHR systems retrofitted in existing dwellings may need to target these higher performance specifications where these buildings often present greater challenges to realising low air permeability values.

In addition, it may be possible to achieve further savings by using a more complex air flow rate control strategy, provided the ventilation rate can maintain the indoor air quality. Further research on this is required.

The simulations indicate that there is potential to realise both energy and CO₂ emission reductions, but real-life savings are only likely to occur if the systems are correctly installed. Briefing Note No. 1 illustrates the need for high quality workmanship associated with the draught-proofing, and correctly-balanced MVHR installation for the E.ON Retrofit Test House, to avoid potential detriment to the energy saving efforts. Quality control and training of installers will be critical to optimising the operation of these systems.

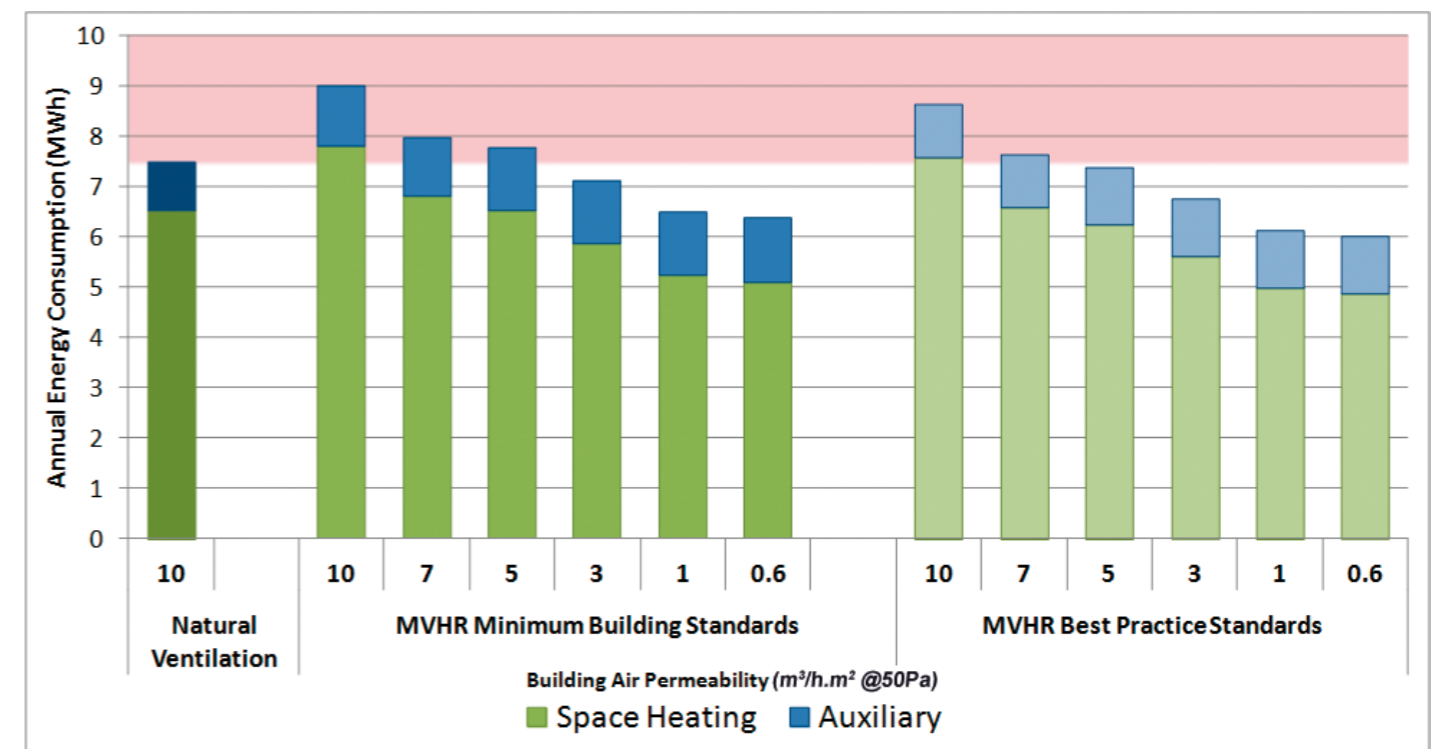


Figure 2: Modelled annual space heating and auxiliary energy consumption of the E.ON Retrofit Test House

Conclusions

A modelling investigation has considered the effect of airtightness on energy and carbon savings with MVHR systems:

- Existing dwellings featuring MVHR must be made more airtight if overall energy savings and CO₂ emission reductions are to be achieved although the requirement is slightly less onerous for systems specified to Best Practice Standard. The detailed performance may differ for other dwelling types.
- Better airtightness is needed in order to achieve overall CO₂ emission reductions because the MVHR system runs on electricity, which is more carbon intensive than the gas that would be used by typical space heating systems. Since existing dwellings present greater challenges to achieving airtightness, higher performance specifications should be used for retrofitted MVHR systems.
- The operational performance of real systems installed in existing dwellings will be adversely affected if the installation process is not undertaken to a sufficient standard. High quality workmanship is critical to ensure that energy savings and CO₂ emission reductions can be achieved in practice.

Recommendations

- The airtightness of existing dwellings must be improved when installing MVHR systems to maximise energy savings and carbon emissions reductions.
- Retrofitted MVHR systems should be specified to the highest levels of performance parameters to cope with the higher air permeability often demonstrated by existing dwellings.
- Further research is required to understand the relationship between MVHR systems and airtightness levels in other dwelling types, and establish the required air change rate to maintain indoor air quality.
- An approved installation process or standard of quality control should be exercised to ensure the optimal operation of the installed systems.
- When carrying out airtightness improvements to properties, care should be taken to ensure an appropriate air supply to combustion appliances.



Figure 3: Modelled annual space heating and auxiliary CO₂ emissions of the E.ON Retrofit Test House

Impact of the order of domestic retrofit on long-term energy and carbon savings

Authors: PFG Banfill, SA Simpson, DL Loveday and K Vadodaria

Findings from the CALEBRE Project BRIEFING NOTE NO. 3

Key messages and findings

The operational performance of individual technologies retrofitted for improving domestic energy efficiency depends on the other energy-saving systems present in the home. This makes it important to consider the order in which a suite of retrofit measures are installed to ensure that optimal energy and carbon emission reductions are achieved. Carbon dioxide emissions can stay in the atmosphere for 200 years, therefore any complacency about reducing current emission levels increases the scale of the future challenge. The early achievement of significant energy and CO₂ reductions, through measures such as wall insulation or improved glazing, can help mitigate this challenge by yielding greater long-term benefits through higher cumulative savings. Retrofit programmes, such as the Green Deal, should therefore consider the long-term implications associated with the order of retrofit.

Context

With the launch of the UK Government's Green Deal for improving domestic energy efficiency, the retrofit market for existing homes is becoming increasingly significant. The Green Deal finance will be available for a selected suite of retrofit measures that will be recommended following the Energy Performance Certificate survey of each individual dwelling. However, for a variety of reasons, including financial factors, homeowners may choose to carry out home energy improvements through mechanisms other than the Green Deal, for example via a piecemeal DIY approach that may be protracted over several years (Haines et al, 2010). Whether carried out in a piecemeal or a packaged manner, the operational performance of each retrofit measure is dependent on the other measures in place. Hence, the interaction between systems and their impact on the property needs to be assessed. The CALEBRE research project undertook a study to assess three orders of installation for a selected range of energy retrofit technologies. The aims were to:

- Understand how the operational performances of individual technologies are affected by the order of retrofit
- Identify factors which optimise a long-term retrofit strategy to reduce CO₂ emissions

What we did

A dynamic thermal modelling exercise was conducted, based on the E.ON Retrofit Test House, to assess the energy and CO₂ reductions achieved by applying a selected range of energy retrofit technologies in different orders.

The E.ON Retrofit Test House (Figure 1) was built as a replica of a 1930s semi-detached dwelling. Three orders of retrofit, representing the priorities and needs of different householders, were chosen (Table 1). The 'insulation-driven' order was based on firstly reducing the need for heating, then secondly installing an appropriately-sized boiler. The 'affordability-driven' order was determined by capital costs, installing lower cost measures first. The third order started by implementing technologies predominantly reliant on the expertise of a professional installer, hence the approach was called 'experienced installer driven'.

These three orders assumed the application of a theoretical retrofit timeline, spanning a 25-year period, from 2012 to 2036, inclusive. Measures were installed over seven stages at three year intervals. The term 'base case' means no retrofit measures at all.



Figure 1: The E.ON Retrofit Test House which is being used for trialling of CALEBRE technologies

TABLE 1: ORDERS OF RETROFIT			
Improvement stage	Insulation driven	Affordability driven	Experienced installer driven
Stage 1 (2015)	Energy efficient lighting (CFL)	Energy efficient lighting (CFL)	Initial draught-proofing ²
Stage 2 (2018)	Loft insulation ¹	Loft insulation ¹	Double glazing ¹
Stage 3 (2021)	External wall insulation ¹	Ground floor insulation ¹ & initial draught-proofing ²	Reduced size boiler replacement ⁵
Stage 4 (2024)	Double glazing ¹	Reduced size boiler replacement ⁵	Loft insulation ¹
Stage 5 (2027)	Ground floor insulation ¹ & initial draught-proofing ² double glazing ¹	Ground floor insulation ¹ & initial draught-proofing ² double glazing ¹	External wall insulation ¹
Stage 6 (2030)	Further draught-proofing ³ & installation of MVHR ⁴	External Wall insulation ¹	Ground floor insulation ¹ & energy efficient lighting (CFL)
Stage 7 (2033)	Reduced size boiler replacement ⁵	Further draught-proofing ³ & installation of MVHR ⁴	Further draught-proofing ³ & installation of MVHR ⁴

1. Thermal properties for external constructions and glazing fittings are upgraded as follows:
 - solid brick walls (original U-value 1.7 W/m².K) externally insulated to 0.30 W/m².K
 - 270mm loft insulation installed to U-value 0.16 W/m².K, installed at ceiling level
 - ground floor (original U-value 0.6 W/m².K) insulated to 0.25 W/m².K
 - single glazing (U-value 5.5 W/m².K including frame) replaced by double glazing (U-value 1.5 W/m².K including frame)
 2. This assumes the background infiltration level has been reduced from 0.75 ach⁻¹ to 0.50 ach⁻¹ through straightforward measures (e.g. draught-proofing windows, doors, etc)
 3. This assumes the background infiltration level has been reduced to 0.25 ach⁻¹ through more extensive draught-proofing efforts (e.g. sealing the ground floor)
 4. MVHR represents Mechanical Ventilation with Heat Recovery
 5. Existing non-condensing boiler (88% efficiency) replaced by new condensing boiler (90% efficiency)

What we observed

The modelling study revealed that, whilst the annual energy consumption at the end of the timeframe (2036) is similar for all three orders of retrofit, the previous improvement stages show a large variation in the magnitude of the energy reductions (Figure 2).

Far from being simply attributable to the capabilities of the various retrofit technologies, on closer inspection it is apparent that the energy saving potential of an individual technology differs depending on the prior installation of other improvement measures. For example, the Stage 2 installation of double glazing for the experienced installer driven order reduces the annual energy consumption from 39.1 MWh to 32.8 MWh, compared to the Stage 4 reduction from 35 MWh to 26.2 MWh for the insulation driven order; the energy saving demonstrated by the former (6.4 MWh) is 27% less than the energy saving demonstrated by the latter (8.8 MWh). Assuming natural gas costs 4p/kWh, the reduction in annual energy bills therefore varies by almost £100, and potentially more at higher fuel prices. This means that the same measure, installed in the same house, will demonstrate different payback periods depending on the preceding retrofit measures. This has potential consequences for the Green Deal, in terms of that measure's ability to meet the golden rule where expected financial savings must be equal to or greater than the installation costs attached to the energy bill.

It is important to note that Figure 2 illustrates dependency of the energy-saving potential of individual technologies upon prior-installed measures, together with the benefits of the bigger-saving measures such as double glazing and wall insulation. Figure 2 does not illustrate ideal or preferred orders of retrofit, and should not be interpreted in that way.

Replacing the boiler early in the retrofit order means that subsequent heat-saving measures which reduce the load on the heating system consequently cause the boiler to become oversized and operate less efficiently. This is demonstrated by Figure 2, where the experienced installer driven approach (boiler replaced in Stage 3) has a slightly higher final annual energy consumption compared to the insulation driven approach (boiler replaced in Stage 7). Relative to the 2012 baseline, these two orders achieve a 59% and 62% reduction in annual energy consumption, and 53% and 55% reduction in CO₂ emissions, respectively. This difference might appear marginal, but simply considering the annual building performance fails to consider the long-term implications of the efficiency improvements.

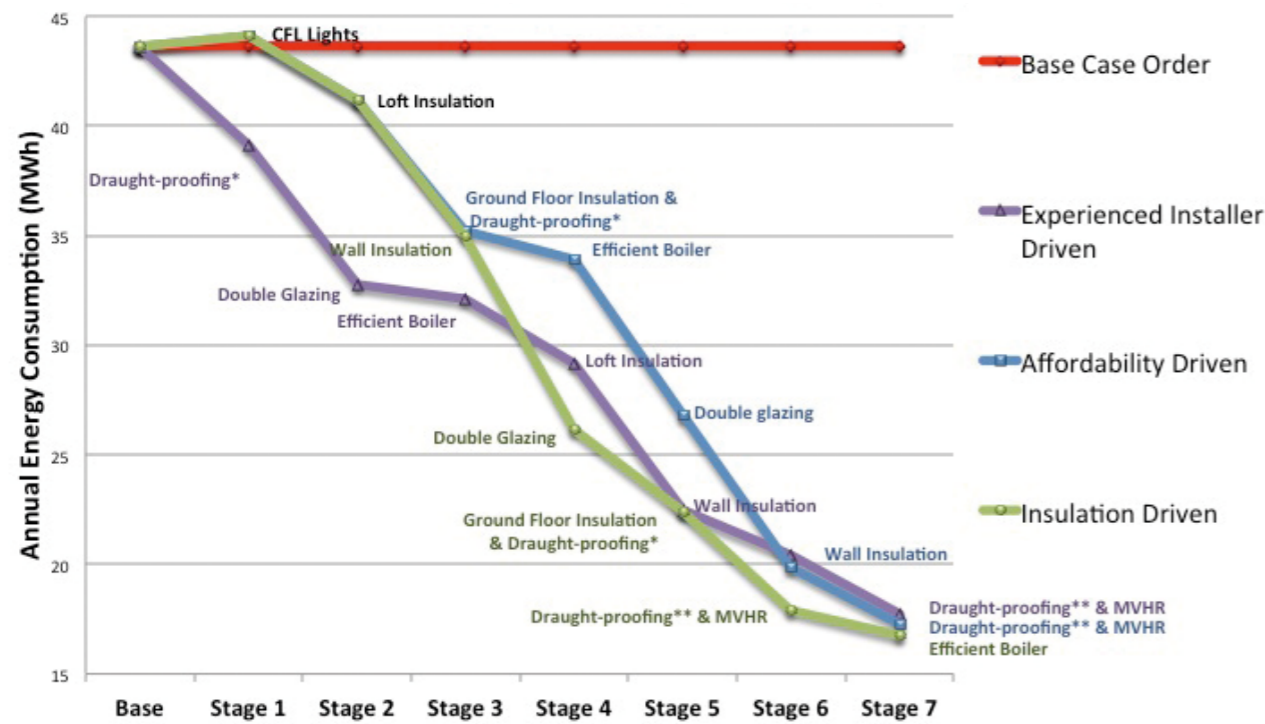


Figure 2: Dependency of energy saving potential of individual technologies upon prior-installed measures

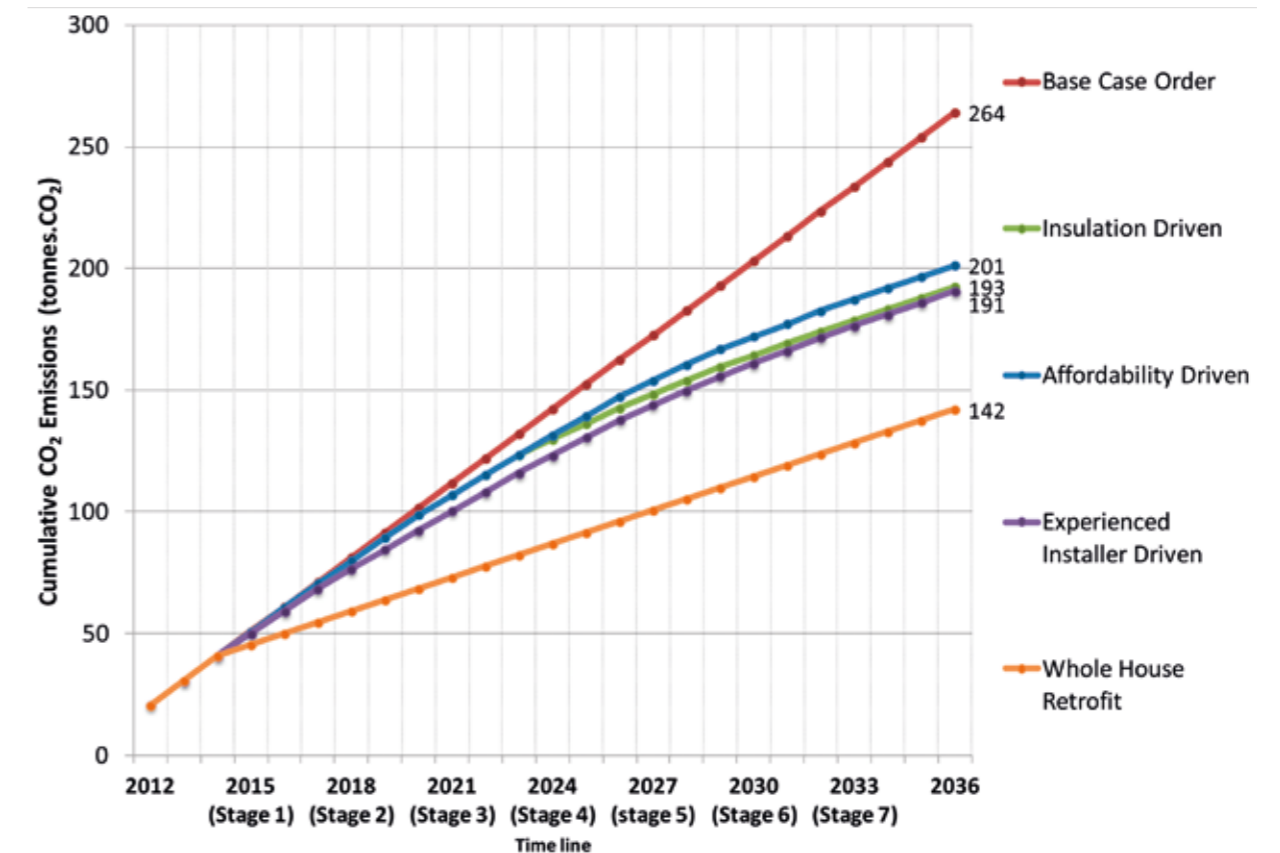


Figure 3: Cumulative CO₂ emissions through Stages 1 to 7 for various orders of retrofit

CO₂ emissions can remain in the atmosphere for up to 200 years, therefore achieving reductions sooner rather than later is important to mitigate the extent of the future challenge. Double glazing and wall insulation achieve the greatest reductions, in both annual energy consumption and CO₂ emissions, for all three orders. Achieving these significant improvements early in the retrofit process yields greater benefits with regards to the cumulative emissions (Figure 3). Replacement glazing is the second measure in the experienced installer driven order, which means this order gives the lowest annual energy consumption and CO₂ emissions as far as Stage 4 and, despite the detrimental effect of the oversized boiler towards the end of the retrofit process, gives the lowest cumulative emissions throughout the whole process. Although there may be no significant difference in cumulative emissions for the three orders (which assume identical retrofit installation timelines), comparing a whole house retrofit (based on the simultaneous application of all the retrofit measures), undertaken in Stage 1, to the base case (assuming no retrofit measures at all), shows a 46% reduction in cumulative CO₂ emissions. This compares with a reduction in the range of 24-28% for the three orders of retrofit.

Conclusions

The modelling work reported in this briefing note considers the impact of the order of domestic retrofit on energy and carbon savings.

- Findings suggest that the benefits and payback times of individual measures vary according to the preceding energy efficiency measures that have been applied. This will have a significant impact in terms of the Golden Rule of the Green Deal.
- The modelling suggests that early implementation of measures that achieve significant reductions in annual energy consumption and CO₂ emissions, such as external wall insulation and double glazing yield the greatest benefits with regard to the cumulative savings.

Recommendations

1. Homeowners need to be aware of the implications of the order in which they apply energy efficiency retrofit measures to their homes
2. Green Deal providers need to account for the variation in payback times associated with different individual measures relative to the other measures already in place.
3. Greater cumulative energy and CO₂ savings can be realised by early installation of those retrofit measures which yield the biggest savings

References / further reading

Haines, V.J.A., Mitchell, V.A. and Mallaband, R.A.L. (2010) Using a Practice-Orientated Approach to Inform the Design of Energy Efficiency Measures for Older Homes. ERSCP-EMSU Conference, Delft, 25-28 October 2010. Pages 1-17

Banfill, PFG, Simpson, SA, Haines, VJ and Mallaband, RAL (2012) Energy-led retrofitting of solid wall dwellings – technical and user perspectives on airtightness. Structural survey, 30, (3), 267-279

Simpson, S.A. and Banfill, P.F.G., (2012) The importance of the order of installation of retrofit measures in optimising long-term energy and CO₂ reductions, Proceedings of Retrofit 2012 Conference, Salford, UK

Heat pumps for energy efficiency refurbishments of homes – reducing the hassle to householders

Authors: RE Critoph and NJ Hewitt

Findings from the CALEBRE Project BRIEFING NOTE NO. 4

Key messages and findings

The CALEBRE heat pumps have been designed for ease of retrofit, suitability for working efficiently with existing radiator systems in homes, and take into consideration householder appeal. Initial tests have been encouraging, and with a little further development, they are expected to become available in the near future as commercial products for UK domestic refurbishment.

Context

The suite of technologies currently available for domestic refurbishment includes heat pumps. However, the majority of heat pumps available in the market at present require the removal of the existing radiator system and installation of under floor heating to offer the best energy efficient heating. This can be disruptive, expensive and lacking in user appeal, particularly in the case of listed / character properties, since it requires the removal and replacement of existing floor coverings.

Is it possible to have energy efficient heat pumps that can supply high delivery temperatures and be deployed with the minimum of householder disturbance?

To investigate these questions in detail, the CALEBRE research team have designed and laboratory-tested three air source heat pumps aimed at domestic refurbishments.



What we did

The CALEBRE project teams at Warwick University and Ulster University have developed one gas-fired and two electric air source heat pumps, respectively. These heat pumps have been designed and manufactured, taking into consideration the technical challenges of domestic refurbishment and householder appeal. One of our aims is to develop air-source heat pumps that utilise the existing radiators in a dwelling. Warwick's adsorption concept is an affordable air source heat pump that can replace a conventional gas-fired boiler and reduce gas consumption by over one third. In volume production, the excess capital cost is expected to be no more than £1,000 leading to payback times of around three years. In order to overcome the typically large size of adsorption units and enhance their suitability for domestic deployment, a novel shell and micro-tube construction sorption generator with lower thermal mass but with equivalent heat transfer was developed. A further aim is to have an indoor unit no bigger than a standard boiler, and with a small, external evaporator (Fig 1). A spin-out company (Sorption Energy) launched as a result of the CALEBRE project is inviting investment capital to develop products in collaboration with boiler manufacturers.

The University of Ulster team has developed an economised vapour injection (EVI) compressor heat pump and an expansion turbine heat pump (Fig 2). In addition to increased compressor power, a loss of capacity occurs with use of the isenthalpic expansion valve (throttle valve) when a traditional vapour compression heat pump operates in a higher temperature retrofit regime. The EVI heat pump operates as a modified two stage compressor with subcooling to avoid the loss of capacity and with reduced compressor power. Alternatively, power recovery from a turbine can potentially alleviate this problem. Again focussing on domestic retrofit, a compact unit was developed in conjunction with industry.



Figure 1: Illustration of CALEBRE gas-fired heat pump (developed at Warwick University)

What we observed

Gas-fired heat pump

The unit was tested inside an environmental chamber under a range of ambient conditions to EU standards. Initial operation successfully produced output water at 60°C, as would be required if utilising existing domestic radiators. The machine has performed well, but with less power output than wanted.

Economised Vapour Injection (EVI)

The electric air source heat pump based on EVI technology was also tested in an environmental chamber under a range of ambient conditions to EU standards. A limited field trial realised a seasonal COP of 3.7.

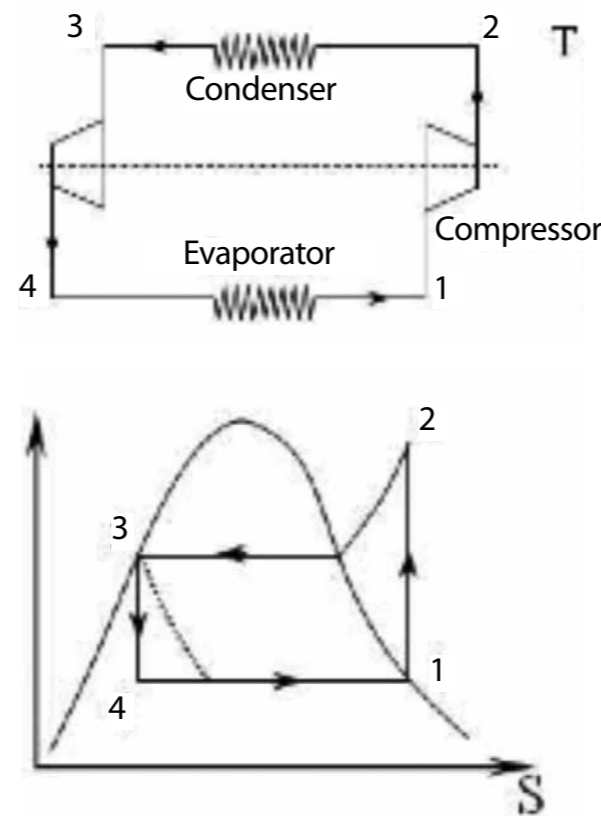
Compressor-Expander

Initial results were promising, but deteriorated over time as internal refrigerant leakages and internal heat transfer between turbine and compressor negated expander gains. A new unit has been developed with improved design, limiting unwanted internal heat transfer and eliminating turbine / compressor refrigerant leakage, leading to superior compression and expansion efficiency. Initial laboratory results were promising when tested to EN14511 test standard.

Both EVI and Rotary Expander electric heat pumps would also benefit from enhanced lower temperature radiator concepts. Reliability of the rotary unit is improving and performance will improve with longer run times and increased understanding of the internal interactions. The EVI compressor is now well established but its increased complexity challenges defrost strategies and the role of variable speed is an important development to maximise efficiency and flexibility of operation. Extensive laboratory and field trials will lead to greater reliability and social acceptability. Joint efforts with manufacturing specialists within the CALEBRE project will reduce overall capital costs. It is then expected that proven efficiencies will become commercial realities, and that both types of system will find opportunities in homes that have reduced heating loads. Thus, whether it is the better use of gas resources or management of variable electricity resources, heat pumps are a socially acceptable means for domestic space heating.



Figure 2: Prototype of CALEBRE electric EVI heat pump (developed at Ulster University)



Conclusion

Our research work has demonstrated that a gas-fired heat pump to replace condensing boilers that will be acceptable to consumers is technically feasible. This heat pump can deliver 33% gas savings when compared to conventional boilers when operated with radiators of sufficient capacity, giving a payback time of less than three years. As a result of discussions with potential manufacturing partners, effort is being directed into development of the thermal compressor that is the novel part of the whole system. The thermal compressor will form the heart of a complete system with around 8kW output and COP (based on gas gross calorific value) of better than 1.2.

The opinion of National Grid is that there is a need for either hybrid or gas-fired heat pumps well into the future, if only to avoid major electricity distribution upgrades and that both gas and electric heat pumps are needed in a sustainable but affordable future.

Recommendations

1. For gas-fired heat pumps, which are particularly suited to retrofit applications, the route to commercialisation is in partnership with boiler manufacturers, rather than in competition. Support and investment is needed.
2. Advanced electric heat pumps will overcome the drawbacks of many conventional systems and will provide low cost heating in dwellings that would previously have required major refurbishment to benefit from heat pump technology.
3. Parties interested in potential investment and further development should contact the CALEBRE team.

Energy efficiency refurbishments – householders’ appetite for improvement, and tolerance for change

Authors: VJA Haines, V Mitchell, R Mallaband, DL Loveday and K Vadodaria

Findings from the CALEBRE Project BRIEFING NOTE NO. 5

Key messages and findings

Refurbishing people’s homes in an acceptable way is a complex process. Householders present a range of social and technical barriers to easy retrofit. By taking these into consideration, it is possible to better design retrofit policies and practices that appeal to householders and align with their lifestyles.

Context

We need to make our homes more energy efficient in order to reduce our energy demand, lessen household fuel bills, and improve our comfort. At the same time, this can help reduce carbon emissions associated with use of fossil fuels and thus help tackle climate change. Domestic energy efficiency refurbishment is expected to gain momentum with the launch of the Green Deal, a government-backed initiative which helps meet the upfront cost of installing technologies that save energy in our homes. But how can we encourage energy refurbishment of homes in ways that are acceptable and appealing to householders? What are the barriers, motivators and enablers to domestic energy efficiency refurbishments? What can be learnt from householders’ past improvement practices so that refurbishment programmes like the Green Deal can be targeted in a more effective way? How can we use this knowledge to better inform future energy improvements? To investigate these questions in detail, the CALEBRE research project undertook an in-depth qualitative survey of householders living in solid wall properties.



What we did

Our study took a user centred design approach, in conformance with ISO 9241-210: 2010. Semi-structured interviews of 20 households (66 occupants) living in owner-occupied hard to treat, solid wall houses in the East Midlands area of the UK were conducted to uncover their reasons for carrying out past home improvements with a view to understanding the barriers and motivations towards future refurbishments. Transcribed interview data were analysed using a thematic analysis approach using NVivo qualitative data analysis software. Comments were identified and sorted into themes that emerged from the data.



What we observed

The thematic analysis of the study data has highlighted a range of interrelated, and sometimes rather intangible barriers, to making home improvements to older, hard to treat properties. These expand and elucidate the three primary barriers of: information and awareness; hassle; cost identified by the Energy Saving Test (EST) (2011). Our findings indicate that people’s motivation to carry out refurbishment was not so much to save energy but rather the desire to improve comfort and the need to repair. Although many households undertook refurbishment works at the time of house purchase, on-going improvements were carried out at intervals in a piecemeal manner. Very few homeowners were willing to move out of their property for refurbishment, unless there were health issues. There was a desire to maintain and restore original features of the house, for example, single glazed character windows, despite them being draughty and energy-inefficient. Many householders were found to prefer carrying out improvement works themselves. However, when required, professionals were chosen on the basis of price, trust, recommendation and length of time the professional was known to them. Unknown professionals generally were not being given work. Tables 1-4 summarise these and further key findings from our analysis.

Motivation, timing and cost
Saving energy is not a priority; the need to repair or desire for comfort drives most improvements
Most major work is done at purchase, with on-going improvements at intervals
Cost often prevents work being done, or done in keeping with the age of the property

Table 1: Refurbishment and motivation, timing and cost – key findings

Original features
There is a desire to maintain and restore original features in older houses
Windows are important character features to householders – some retaining single-glazed, draughty windows over modern ones
There may be a lack of knowledge by professionals on how to deal with solid wall properties and their character features

Table 2: Refurbishment and original features – key findings

Refurbishment process
Most householders complete improvements piecemeal – the order of retrofit varied
Often a bulk of work is done before moving in, enough to achieve occupation
Few are prepared to move out for a refurbishment, unless there are health issues

Table 3: The refurbishment process itself – key findings

Trust issues
Few householders would accept unknown professionals
Professionals chosen on price, trust, recommendation and time they were known
The same trusted professional used for variety of jobs, in preference to lesser known specialists
Many householders do improvements themselves

Table 4: Refurbishment and trust issues – key findings

Further examination of the specific issue of airtightness and ventilation was conducted. Attitudes of householders can be summarised as follows:

Air flow and freshness

- Householders are keen to maintain air flow, even if it loses heat
- Airtightness and mechanically ventilated air were viewed negatively, but the concept was more positively received when explained

Open fireplaces

- 75% of our households had some form of open chimney / vent. Many people were not prepared to lose functionality of these; period feature fireplaces were important aesthetically

Door closing practices

- There are strong habitual practices of closing internal doors, eg to reduce internal noise, to isolate rooms, to keep pets and young children in particular areas, or for privacy

Damp

- Ventilation is used to control humidity, eg after a shower or in place of a dehumidifier
- Householders expressed feelings that draughts kept a house adequately ventilated and healthy

This component of the CALEBRE investigation suggests that retrofitting an MVHR system into a house should also consider how the house will be used. Clear communication will be critical if the benefits of a more airtight house and mechanical ventilation with heat recovery (MVHR) are to be introduced.

Conclusions

This research has identified a range of social and emotional barriers that can cause inertia or even halt energy efficiency refurbishment projects for many years. The Green Deal is designed to alleviate the financial barriers to making energy saving improvements to existing homes. However, analysis of the interview data suggests that many householders would still resist taking advantage of the scheme because of the wider social and emotional barriers to change. Factors relating to personal capacity, perceived difficulty of a job, likely disruption and inability to reach consensus with a partner have all been highlighted as reasons why home improvements have not been undertaken as expediently as they might have been.

The barriers identified in this research show a range of interrelated factors, many particular to older properties. The vast majority of the householders interviewed had chosen to live in older properties at least partly because of their character and appearance. Features had been lovingly restored and preserved even in the face of compelling financial reasons to modernise.

Recommendations

- There is clearly a need to better understand the priorities, values and aspirations of householders who choose to live in harder to treat homes. This is needed in order to equip both policymakers and building professionals with the specialist knowledge that is needed to sympathetically retrofit energy saving measures whilst maintaining the character of the house and overcoming the idiosyncrasies of older properties.
- The depth of property-related knowledge held by many householders regarding their older properties was surprising, causing great frustration when professionals did not share the same specialist knowledge. Clearly, competent and appropriately skilled professionals will be required to meet the expectations of these householders.
- Although a number of barriers have been identified, there are clearly opportunities for retrofitting, given the range of home improvements already being undertaken, many of which relate to the energy usage of the home. Design of refurbishment policies and practices should take into consideration the findings uncovered in the CALEBRE research project.

References / further reading

Mallaband, RAL, Haines, V and Mitchell, V (2013) Exploring Past Home Improvement Experiences to Develop Future Energy Saving Technologies. Methods for Studying Technology in the Home Workshops, ACM SIGCHI Conference on Human Factors in Computing Systems (CH2, Paris, France 27 April – 2 May

Banfill, PFG, Simpson, S A, Haines, V J and Mallaband, RAL (2012) Energy-led retrofitting of solid wall dwellings – technical and user perspectives on airtightness. Structural survey, 30, (3), 267-279

Haines, VJA, Mitchell, VA and Mallaband, RAL (2012) Merging a practice-orientated approach with an engineering-driven product development: A case study on home improvement. Journal of Design Research. Special Issue on Design, Sustainability and Behaviour, 10 (1/2), 28-49

Advanced technologies: Innovative materials for humidity control

Authors: M Hall, E Tsang and S Casey

Findings from the CALEBRE Project BRIEFING NOTE NO. 6

Key messages and findings

Three mesoporous silica (MS) samples were selected as template materials for designing high-performance desiccants to give rapid-response temperature and humidity buffering in closed environments. The MS materials had more than two orders of magnitude greater humidity buffering than those traditional interior building materials (e.g. painted gypsum plaster) due to their high vapour storage capacity and high dynamic vapour sorption (DVS) response rates. This clearly suggested the mesoporous structure of controlled porosity is promising to give good response for temperature and humidity buffering in closed buildings.

Context

Closed environments (over a range of scales) often require the interior psychrometrics to be mechanically controlled by heating, cooling, humidification and dehumidification (i.e. the HCHD load). Examples of relevant closed environments include storage vessels, automotive and aerospace cabins, archives, museums, and occupied buildings. A high level of heating-cooling operational energy efficiency is typically sought by designing for i) very low air infiltration or adventitious ventilation, and ii) very high thermal resistance of the surrounding fabric [1-4]. Without careful design, this approach can have the opposite (i.e. negative) effect on both the HCHD operational energy efficiency and the quality of the indoor air [5-7]. The latter is defined with respect to the permitted upper/lower values for dry bulb temperature and relative humidity, either for occupant thermal comfort or simply the required ambient conditions [2, 8].

The required level of both temperature and humidity buffering, and for any of the given applications, could be achieved if the hygrothermal function properties of a candidate material could be directly correlated with its micro structural characteristics. The aim of this research component of the CALEBRE Project was to better understand this correlation, and to begin engineering a nano-composite starting with a high level of performance in relative humidity buffering for application in controlled closed environments. This required selection of a candidate base material whose internal pore geometry could be synthesised and fine tuned, i.e. mesoporous silica (MS). The composite could later be applied, for example, as a surface coating technology, in a fluidised bed application, or as a porous solid composite.

What we did

Four different mesoporous silica (MS) samples were synthesised for assessment as candidate rapid-response desiccant materials. Their behaviour was compared with that of conventional desiccants. Pore geometry was characterised and validated using SAXRD, BET, BJH, and HRTEM (see Fig 1). Thermophysical properties were characterised using MTPS and DSC. Vapour storage and sorption / desorption response rates were characterised using modified DVS techniques. Three mesoporous silica materials were selected as coatings to provide humidity buffering in retrofitted 'closed' environments (see Fig 2). Simulation was carried out using the hygrothermal numerical model WUFI Plus v2, and validated against experimental results emerging from a series of physical models that were conducted inside a climatic chamber. Parametric analysis of key variables including ventilation rates, moisture loads and coating surface area using numerical simulation was then undertaken.

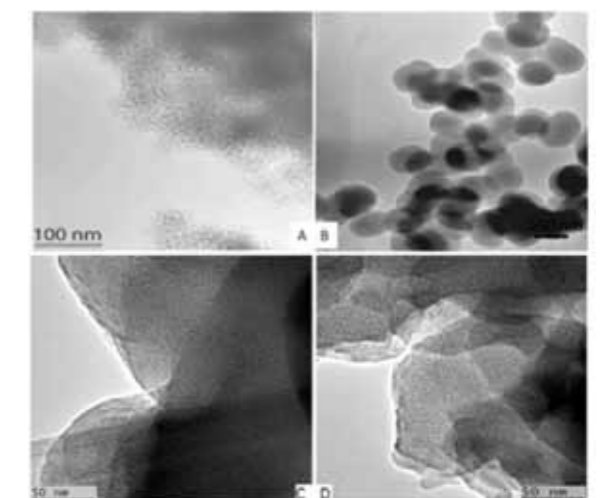
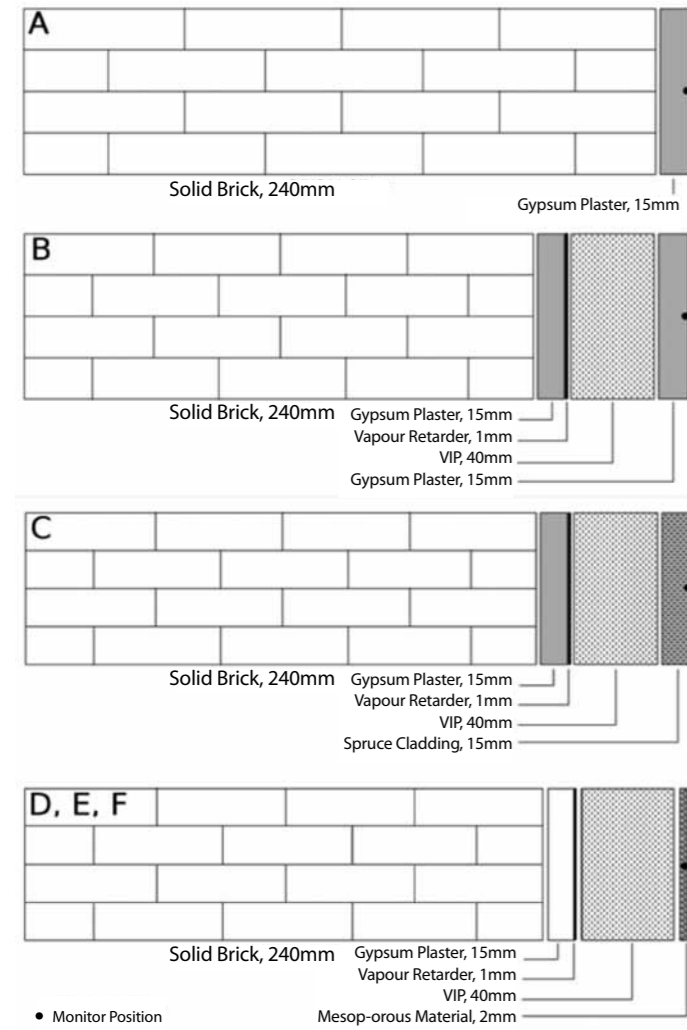


Fig 1: HRTEM brightfield contrast micrographs of the four mesoporous silica samples



What we observed

It was found that the volume and mean diameter of the mesopore network are directly related. When their values were increased, it would cause a proportional decrease in macropore volume and bulk porosity suggesting that the pore wall thickness decreases at larger mesopore volume. The DVS response time, t_{emc} gave a positive logarithmic relationship with both mesopore diameter and mesopore volume, whilst vapour permeance appeared to be inversely related. All MS samples had a significantly higher vapour storage capacity and quicker DVS response rate than the conventional desiccants including silica gel, zeolite, molecular sieve and bentonite (see Figs 3 and 4). The MS materials showed consistent reduction in fluctuating relative humidity amplitudes for both occupied and unoccupied spaces in daily and annual cycles, providing humidity buffering within ASHRAE thermal comfort limits and a potential reduction in humidification / dehumidification energy demand of up to 100% when compared against a conventional gypsum-lined indoor environment.

Figure 2: Component assemblies for comparative testing for real psychrometric conditions

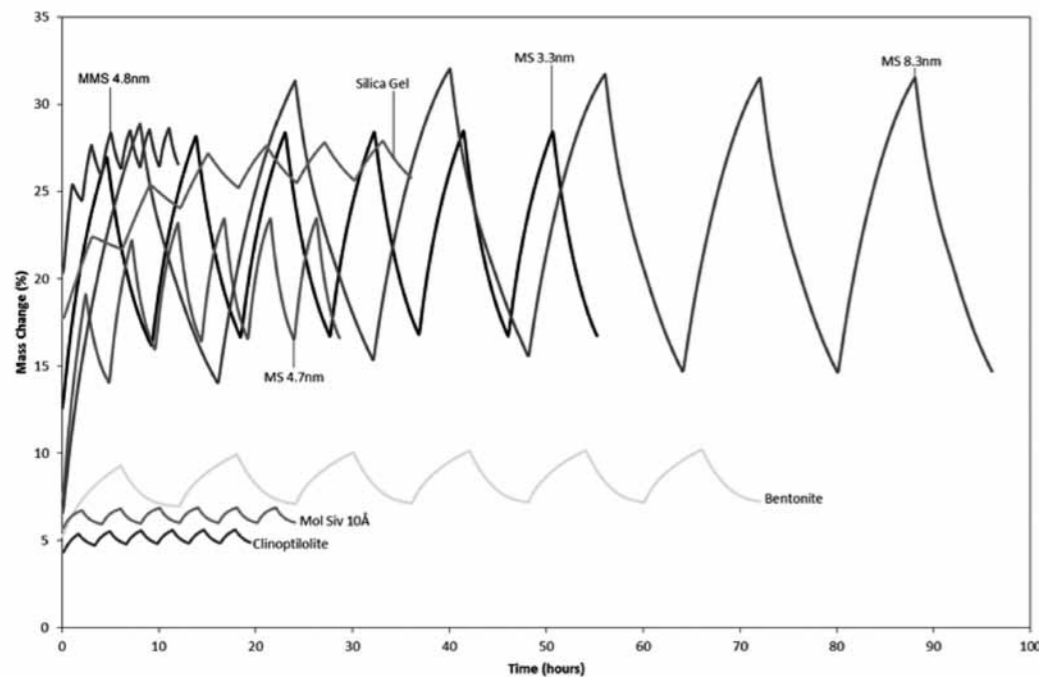


Figure 3: Mean and total range of moisture uptake in the thermal comfort range with normalised time scale for all materials at 23°C

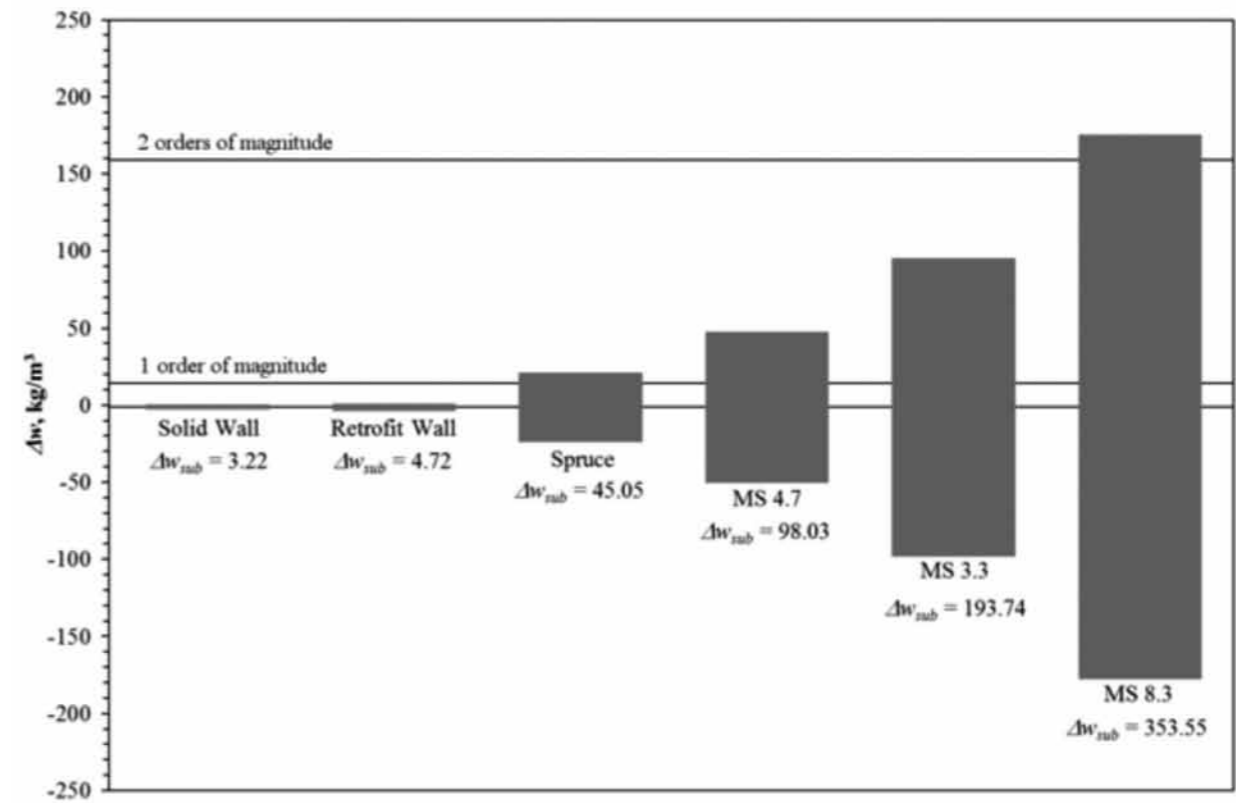


Figure 4: Graph showing yearly range of w_{sub} for comparative simulation

Conclusions

The MS materials show consistent reduction in fluctuating RH_{ie} levels under both partial and full HCHD control in daily and annual cycles, providing humidity buffering within ASHRAE thermal comfort limits. MS materials have been shown to be excellent moisture buffering materials, passively reducing fluctuations of RH_{ie} under a wide range of conditions. They have the excellent potential to improve occupant comfort, improve indoor air quality and reduce the energy demand in buildings. When compared against a retro-fitted gypsum-lined indoor environment there is a potential reduction in humidification / dehumidification energy demand of up to 100% achieved when using an MS material coating.

Recommendations

It is encouraging to establish the fact that mesoporous silica of controlled porosity gives rapid response to temperature and humidity buffering as the proof of concept in this research. The samples used however, are high-purity and laboratory prototypes, which were necessary in order to give direct control over the nano-scale pore geometry and functional properties. The anticipated cost of the material could be high. Research should begin to focus on bulk-scale manufacture of the related materials for deployment not only in the specific applications researched here but for any closed environment, e.g. cars, aircraft, buildings, medical storage containers etc. Not only could a wide range of materials be produced at relative low cost with properties to suit standard applications, but also materials tailored to specific high-end applications. This could ultimately lead to control of moisture and condensation risk within enclosures using relatively small surface areas treated with suitably-engineered mesoporous silica materials.

References / further reading

- [1] Hall M R (Ed.) 2010 Materials for energy efficiency and thermal comfort in buildings (Cambridge: Woodhead)
- [2] CIBSE 2006 Guide A - Environmental Design - 7th edn (London: CIBSE)
- [3] Jayamaha L 2006 Energy-efficient building systems: green strategies for operation and maintenance (New York: McGraw-Hill)
- [4] Bauer M, Mösle P and Schwarz M 2010 Green building guidebook for sustainable architecture (Berlin: Springer)
- [5] Kalamees T, Korpi M, Vinha J and Kurnitski J 2009 The effects of ventilation systems and building fabric on the stability of indoor temperature and humidity in Finnish detached houses *Building and Environment* **44** 1643-50
- [6] Liddament M W and Orme M 1998 Energy and ventilation *Applied Thermal Engineering* **18** 1101-09
- [7] Orme M 2001 Estimates of the energy impact of ventilation and associated financial expenditures *Energy and Buildings* **33** 199-205
- [8] ASHRAE 2009 Handbook - Fundamentals (SI Edition) (Atlanta, GA: ASHRAE)
- [9] Hall MR, Tsang S C E, Casey S P, Khan M A, and Yang H, 2012, 'Synthesis, characterisation and hygrothermal behaviour of mesoporous silica high-performance desiccants for relative humidity buffering in closed environments', *Acta Materialia*, 60 pp. 89-101
- [10] Casey S P, Hall M R, Tsang S C E, Khan M A, 2012, 'Designing a nano-composite material for rapid-response air temperature and humidity buffering in closed environments', *Journal of Building Performance Simulation* – accepted in press
- [11] Casey S P, Hall M R, Tsang S C E, Khan M A, 2013, 'Energetic and hygrothermal analysis of a nano-structured material for rapid-response humidity buffering in closed environments', *Building and Environment*, 60 pp. 24-36

Mapping occupancy and energy use in homes: An advanced real-time location and energy tracking system

Authors: M Gillott and C Spataru

Findings from the CALEBRE Project BRIEFING NOTE NO. 7

Key messages and findings

A principal source of uncertainty in post occupancy evaluation of buildings is the behaviours of the occupants. Therefore, the prime motivation of this research component was to gain an understanding of how sensors could be used for tracking occupancy patterns in order to determine people's activities within domestic environments. A real-time location and energy tracking system was developed by the CALEBRE research team which enabled an accurate understanding of the intrinsic links between occupancy behaviours and energy use, hence enabling the estimation of personalized energy use. The system was also capable of recording how occupancy patterns varied before, during and after retrofit interventions were installed in a test house. This work has facilitated the first documented study of accurate disaggregated occupancy and energy patterns recorded in a family home used for retrofit trials of energy efficiency measures.

Context

Domestic property accounts for approximately 27% of the UK's CO₂ emissions and it is estimated that efficiency gains through behaviour modification could account for up to 25-30% of carbon emissions reduction [1]. It is thus crucially important to consider user energy behaviour in buildings, and particularly methods and technologies that could be used to analyse these behaviours. Disaggregated occupancy and energy data has the potential to estimate personalised energy use by answering the questions 'who, where and when?'

What we did

The University of Nottingham's E.ON Research House, part of the Creative Energy Homes (CEH) project, is a replica 1930s three bed semi-detached property constructed with all the characteristics of that era including the inherent poor thermal performance characteristics that are common to many of the UK's 25 million existing dwellings. The house was lived-in and fully monitored throughout the project to get real-time occupancy data for energy use, environmental conditions and occupant location. The post occupancy evaluation (POE) study included environmental monitoring using a network of temperature and humidity sensors within the house. Electricity use was monitored using whole house, circuit and appliance meters (including lighting). Energy meters were also used to monitor the energy associated with space and water heating. During the field trials, the occupants' behaviour was monitored to determine their real-time occupancy patterns.



Figure 1: E.ON Research House Kitchen. Who? Where? & When? Real-time location and energy monitoring.

This facilitated the accurate analysis of occupancy patterns and space use, ensuring no external influences or changes in behaviour influenced total or partial energy use (such as changes in the number of occupants, personal habits, room use, etc).

A Real-Time Location System (RTLS) using ultra wideband (UWB) radio frequency (RF) technology with high positional accuracy and reliability was used for the tracking of occupants. The system utilised a network of static sensors positioned around the house which picked up the 3D location of compact tags which were carried by the occupants.

What we observed

The monitored data was analysed using C++ computer code in order to determine with high accuracy the full location path of the occupants and their relationships with energy consumption and space use. The data collected was manipulated and translated into a descriptive series of activities performed regularly in the house by the occupants, and then it was related to the corresponding energy consumption values. For each registered sensor event an activity was queried, based on zone / location description and energy consumption status through the detailed monitoring of individual power sockets or lights. Examples of activities considered were: sleeping, cooking, watching television, shower / bath, use of computer, laundry, vacuum cleaning, and switching lights on / off. Figure 3 illustrates a data set for a 24 hour period showing total energy consumption in relation to the total number of occupants in the house.

The detailed occupancy data also enabled us to establish the patterns of time spent in particular spaces within the test house for the individual occupants. These patterns were shown to vary over the course of each day in relation to activities undertaken. Figure 4 shows the aggregate relationship between the floor area of each room and the time spent by a person during a typical day. Each dot represents a recorded location of an occupant. The density of dots therefore indicates the level of occupancy at different locations. In this particular case, the most-used space was the dining room which was used as a home office for the occupant whose data is presented.

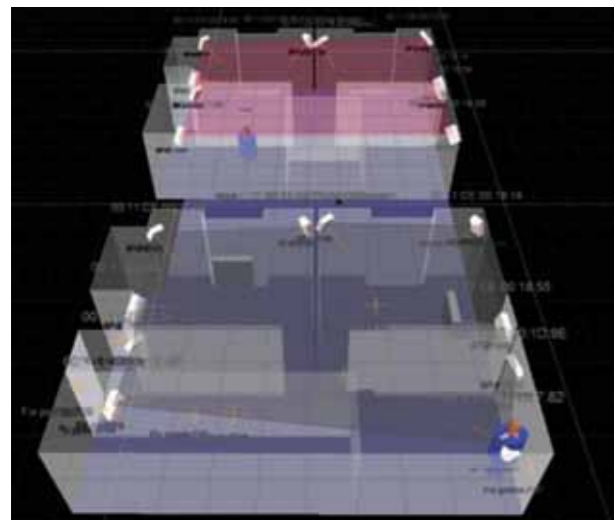


Figure 2: Real-time location and tracking system (occupants in blue). Screen shot of computer visualisation interface showing the ground floor and first floor monitored environments in the E.ON Research House.

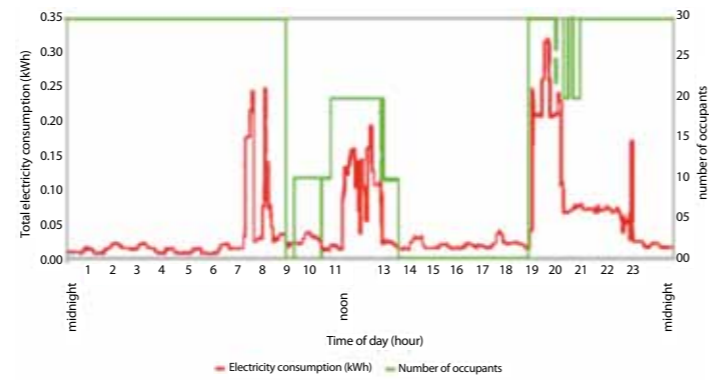


Figure 3: Electrical energy and occupancy data for a typical day in the E.ON test house.

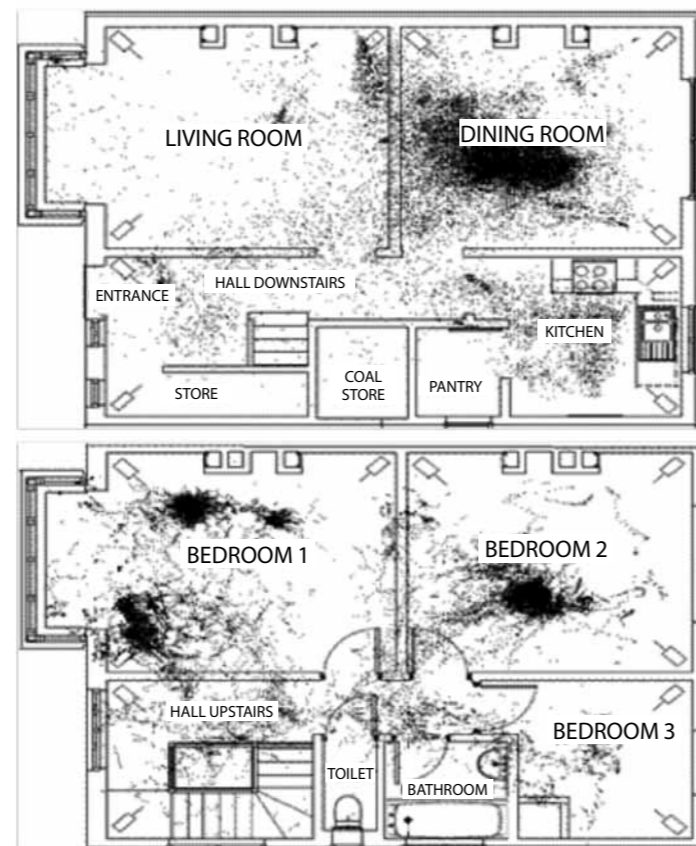


Figure 4: Occupancy mapping example for one person on a typical week day in the E.ON Research House.

Outreach

An example of outreach associated with the project was when BBC Blue Peter presenters Helen Skelton and Barney Harwood were tracked to determine their individual energy wastage over a 24 hour period in the University of Nottingham E.ON Research House. Professor Mark Gillott used black balloons to help the young audience visualise CO₂ emissions resulting from one hour's wasted electricity use due to leaving unnecessary lights on. The real-time location and energy tracking system was used for the experiment (see Figure 6).

Conclusions

A principal source of uncertainty in post occupancy evaluation of buildings is the behaviours of the occupants. The work presented here demonstrated that a real-time location and energy tracking system based on ultra wideband radio frequency technology is capable of locating and tracking occupant location to a good degree of accuracy. This enabled the estimation of personalized energy use. The work also enabled the production of space usage trends through the creation of distribution maps of occupancy and activities. This provided a more in-depth understanding of occupants' responses to environmental conditions and the consequential comfort levels associated with installing retrofit measures / technologies.

The system development was an essential part of a forensic study on the performance of different retrofit measures within a highly instrumented test house. It should be noted that such a system is a specialised research tool, and is not intended for mass deployment due to the system's high capital cost and the need for occupants to wear location devices.

Recommendations

Performance evaluation of buildings studies should, where possible, take account of occupancy patterns and associated energy behaviours. This is especially important for longitudinal studies on in-use performance of buildings and its technologies being used by, or impacting on, different cohorts of occupants. For example, the tenants or owners of a particular home may change, resulting in a potential variation in the number of occupants and their associated behaviour pattern and energy use.



Figure 5: Thermal image of the CEH E.ON Research House after the retrofit of insulation



Figure 6: CALBRE outreach activity, energy behaviours experiment - BBC Blue Peter Climate Week Special (March 2011). In the picture, BBC Blue Peter presenters Helen Skelton and Barney Harwood, Barney the dog and Professor Mark Gillott.

References

1. N Eyre, The impact of lifestyle and social change on the UK energy system, RESOLVE conference, London, June 2009

Further reading

For more information about the Creative Energy Homes Project and the research outlined in this briefing note please contact Mark.Gillott@nottingham.ac.uk

Spataru, C., & Gillott, M. (2012). Using a RTL System based on RFID technology for monitoring occupants domestic energy use and behaviour. In N. M'Sirdi, A. Namaane, R. J. Howlett, L. C. Jain (Eds.), Sustainability in Energy and Buildings. Springer Verlag.

Spataru, C., & Gillott, M. (2011). The use of intelligent systems for monitoring energy use and occupancy in existing homes. Intelligent Buildings International (3), pp. 24-31. doi:10.3763/inbi.2010.0006. Earthscan Journals, Taylor & Francis Group

Gillott, M., Rodrigues, L., Spataru C., (2010) Low Carbon Housing Design Informed by Research. Journal of Institution of Civil Engineers, (Special Issue: Engineering Sustainability) Proceedings of the Institution of Civil Engineers – Engineering Sustainability Vol. 163, Issue 2, pp. 77-87

Gillott, M., Spataru, C., (2009). Best practice in the refurbishment of existing buildings. In: HALL, M., R., ed. Materials for energy efficiency and thermal comfort in buildings. Woodhead Publishing Limited, Cambridge. pp. 649-680

Spataru, C., Gillott, M., & Hall, M. R. (2010). Domestic energy and occupancy: a novel post-occupancy evaluation study. International Journal of Low-Carbon Technologies (5), pp. 148-157. doi:10.1093/ijlct/ctq020

Integrated system design and cost effective manufacturing solution for CALEBRE technologies for domestic refurbishment

Authors: S Ratchev and K Agyapong-Kodua

Findings from the CALEBRE Project BRIEFING NOTE NO.8

Key messages and findings

Through this research, a systems design and manufacturing methodology has been defined. This methodology is capable of scoping out product-process-resource requirements for high volume manufacture of technologies. Due to the high labour cost of the UK, in-house production of heat pumps and vacuum glazing are only economical at high production volumes when semi / full automation is deployed. Models have predicted various volumes and associated cost effective technologies required for manufacturing these CALEBRE technologies.

Context

In the life cycle engineering of manufacturing systems, decisions taken at the product conceptualisation stage commit about 80% of manufacturing resources. As a result, in high labour and facilities cost regions like the UK, there is the need to virtual-test product designs and their implications on manufacturing resources and cost, so that optimal decisions on appropriate coupling of products-processes-resources can be achieved. This work package therefore developed a robust design and manufacturing methodology for cost effective volume production of CALEBRE-based technologies such as heat pumps and vacuum glazings.

What we did

Based on the research needs, an integrated systems design methodology was developed as shown in Figure 1. Data related to the CALEBRE based technologies (gas and electric heat pumps, vacuum glazing) were collected. This led to the development of the product specifications. Based on the data collected, an assembly tree of the products was developed and used as the basis for developing a bill of materials (BoM). The BoMs led to the generation of different process sequences capable of realising the products. After running simulations of different process scenarios, processes with potential to meet product requirements were selected and integrated with their manufacturing resources. Alternative production volume scenarios were experimented with and based on the results obtained from the simulation, product-process-resource combinations of high performances in cost, lead time and volume were selected.

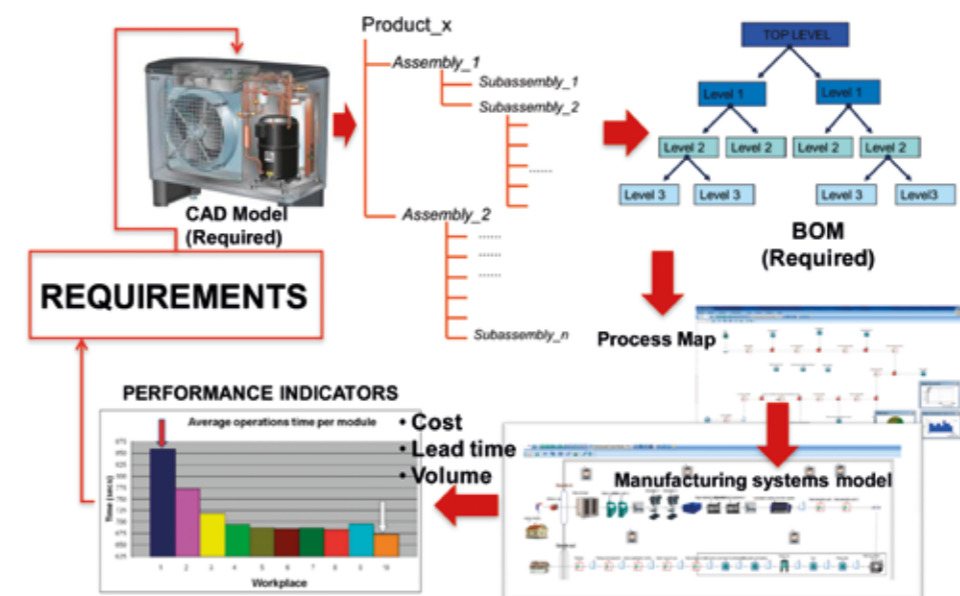


Figure 1: Integrated systems design and manufacturing methodology

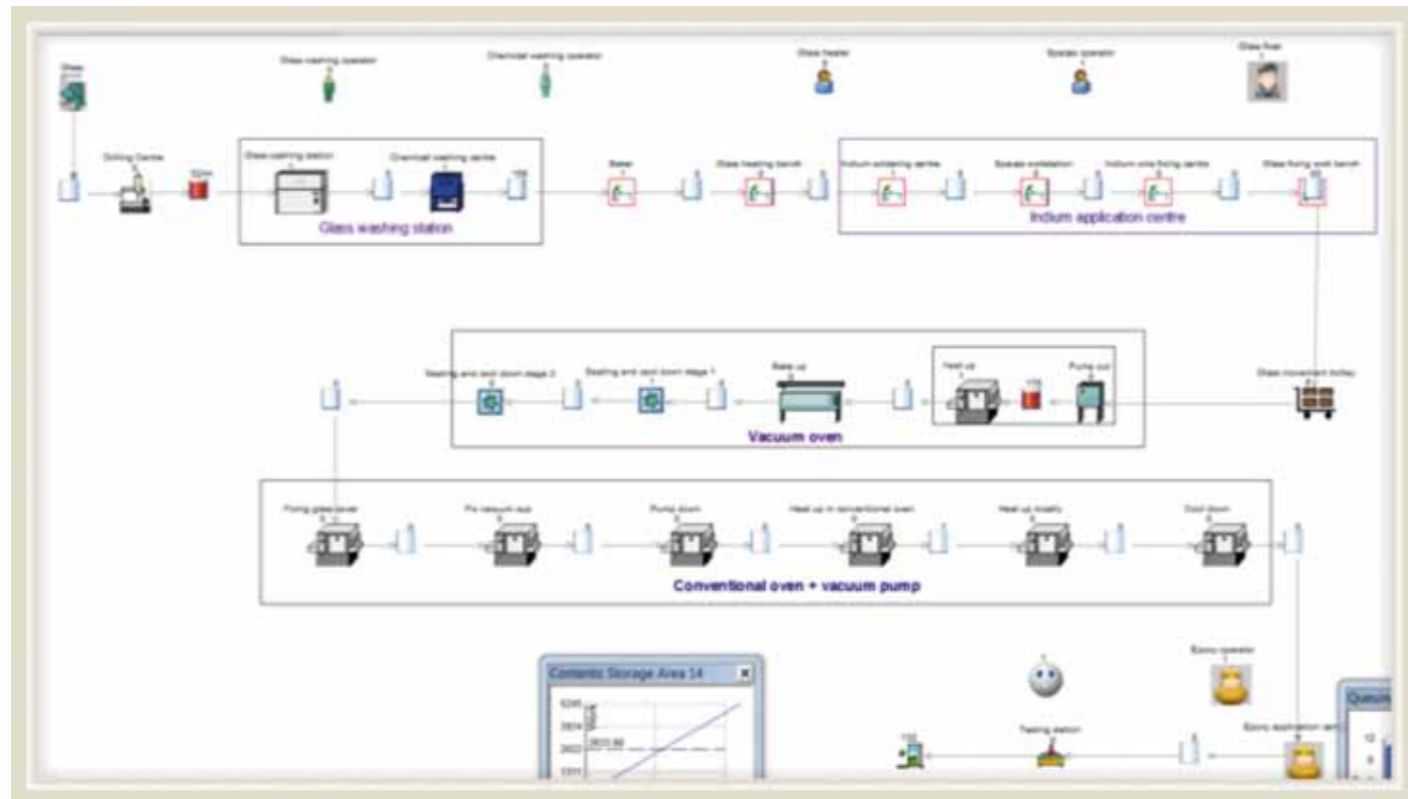


Figure 2: Manufacturing systems model for realising vacuum glazings

What we observed

The manufacturing systems model developed for realising vacuum glazing (VG) is shown in Figure 2. Similar models were created for the manufacturing processes for the gas and electric heat pumps. The models were verified by the technology developers to represent the processes for their laboratory based products. Based on these models, different ramp up scenarios were tested to understand the limitations in the processes when mass manufacturing solutions are considered. Some key observations in ramping up production are described in Table 1. Based on these observations, a mass manufacturing factory solution is proposed as shown in Figure 3.

Production volume/yr	Bottlenecks	Proposed solutions
100	No major bottlenecks	Lab based technology can be translated to production floor
1000	Problems with product size mixes, increase waiting times, more manual operation	Multiple workstations harnessing multiple product flows would be appropriate
500k	High work content at drilling station, vacuum oven and conventional oven limited by their resource capability	Multiple workstations harnessing multiple product flows would be appropriate
800k	Problems similar to 500k demand but in addition indium application and other work stations required more resources	Automation of indium application work station and increased capacity of ovens recommended
1m	Major bottlenecks at all manual work stations	Full automation of production line recommended
8m	Major bottlenecks at all manual work stations	Full automation of production line recommended

Table 1: Observations in ramping up production of vacuum glazings

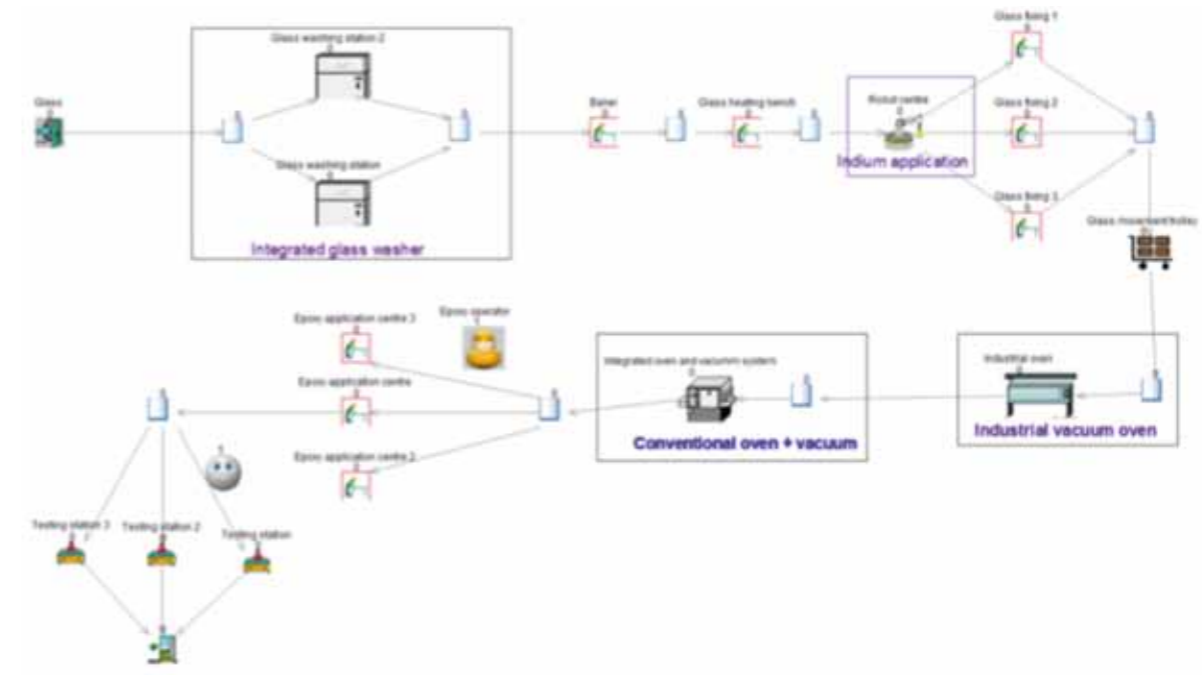


Figure 3: Mass manufacturing factory solution for vacuum glazing

Conclusions

Requirement specifications have been developed for vacuum glazing, electric and gas heat pumps. Based on a review of design and manufacturing methodologies, an integrated systems design and manufacturing methodology was developed. This methodology was applied to the design and manufacture of CALEBRE technologies. From the systems and cost models developed, it serves to indicate that:

1. Manual production facilities based on the developed process models are suitable only for low production volumes of 0-1,000 VG/year. Unfortunately at this production volume, the products are not competitive with equivalent double / triple glazings. However for the expected demand of 8 million VGs/year after 10 years continuous market advancement, semi / full automation is appropriate to reduce the unit cost of the product
2. A manufacturing target cost of £300 is considered for the gas-fired heat pump generator (unit of 4) for volumes of 400k/year. This is realistically achievable for about seven years of full market entrance
3. The current modelling cost of the electric heat pump ranges £4000 - £8000 but equivalent boiler sells at £2000. Long term lower operational cost benefits are to be obtained from the CALEBRE based electric heat pump but the major challenge of electricity and network capacity are yet to be overcome.

Recommendations

To effectively apply the systems design and manufacturing methodology, there is the need for close integration between product developers and manufacturing process designers so that the manufacturing effect of changes to product designs can be captured at early stages. The predicted unit cost for the electric heat pump is based on low entry volumes of 100s per year to about 1,000/year in the first five years. There are, however, challenges with installation, enhanced current network capacity and maintaining positive press image. The products run the chance of competing with equivalent products from Asia and other countries. UK-based production is only recommended for fully automated manufacturing systems realising large volumes of 100 thousand to 10 million products, which is the European market demand. Current gas boilers would have to meet production volumes of about 60,000 units by year seven (three years on market + year four of full commercial trading). VGs stand the chance of mass introduction at competitive prices but full / semi automation of the production line should be considered.

References

- K. Agyapong-Kodua, R. Darlington & S. Ratchev (2013): Towards the derivation of an integrated design and manufacturing methodology, International Journal of Computer Integrated Manufacturing, DOI:10.1080/0951192X.2012.749528
- Jose Zendoia, K. Agyapong-Kodua, Niels Lohse and Mandeep Singh (2012). 'Fundamentals of a co-design methodology for improving the performance of machine tools based on semantic representation'. International Journal of Computer Integrated Manufacturing, DOI:10.1080/0951192X.2013.766936
- K. Agyapong-Kodua, J.O. Ajaefobi, R.H. Weston & S. Ratchev (2012): Development of a multi-product cost and value stream modelling methodology, International Journal of Production Research, 50:22, 6431-6456
- K. Agyapong-Kodua, Rosemary Brown, Rob Darlington & Svetan Ratchev (2012): An integrated product-process design methodology for cost-effective product realisation, International Journal of Computer Integrated Manufacturing, 25:9, 814-82
- K. Agyapong and Svetan Ratchev (2012). 'A methodology for assessing the cost effectiveness of assembly processes'. International Precision Assembly Seminar, IPAS 2012 in special issue Precision Assembly Technologies and Systems, 6th IFIP WG 5.5, Chamonix, France, February 2012
- K. Agyapong-Kodua, R. H. Weston, and S. Ratchev (2012), "The Integrated Use of Enterprise and System Dynamics Modelling Techniques in Support of Business Decisions," Advances in Decision Sciences, vol. 2012, Article ID 804324, 25 pages, 2012. doi:10.1155/2012/804324
- Agyapong-Kodua, K. and Weston, R. H. (2011) 'Systems approach to modelling cost and value dynamics in manufacturing enterprises', International Journal of Production Research, 49:8, 2143-2167
- Agyapong-Kodua, K. Wahid, B and Weston, R. H. (2011). 'Towards the derivation of an integrated process cost-modelling technique for complex manufacturing systems', International Journal of Production Research, 49:24, 7361-7377
- Agyapong-Kodua, K. and R. H. Weston (2009). "Modelling dynamic value streams in support of process design and evaluation". International Journal of Computer Integrated Manufacturing, 22(5), 411-427
- Agyapong-Kodua, K, Adelaide Marzano and Svetan Ratchev (2012). 'The Integrated Use of Enterprise and System Dynamics Modelling Techniques in Manufacturing Enterprises, Elsevier, Procedia CIRP 3 (2012) 543 – 548, 45th CIRP Conference on Manufacturing Systems 2012
10. Garrison, J.D and Collins, R.E (1995). 'Manufacture and cost of vacuum glazing', Solar Energy Vol. 55 No. 3, pp 151-161
11. Collins, R.E and Simko, T.M (1998). 'Current status of the science and Technology of vacuum glazing', Solar Energy Vol. 62 No. 3, pp 189-213

Vacuum Insulation Components for thermal performance upgrade of solid walls homes

Authors: PC Eames, T Hyde, F Arya and S Memon

Findings from the CALEBRE Project BRIEFING NOTE NO. 9

Key messages and findings

The thermal performance of the envelope of solid wall dwellings is in general very poor, and meeting the consequent high heat load is a major contributor to building carbon emissions. Retrofit of current glazing systems, replacing single and double glazing with high performance vacuum glazing, can achieve a significant improvement in thermal performance and also offers the option to increase window to wall area ratios whilst improving the total building envelope thermal performance.

Context

Window energy performance is seen as crucial for improving the thermal performance of the building envelope. In Europe, 44% of buildings still use single glazing and only about 15% of windows use energy efficient glazing. It is estimated that up to 90 million tonnes of CO₂ emissions could be saved annually by 2020 if all Europe's buildings were fitted with double-glazed low emittance (low-e) insulating glass units¹. This saving could be significantly increased if a higher performance glazing system was widely available.

Vacuum glazing is one option which may be used to improve building envelope thermal performance. It consists of two or more sheets of glass hermetically sealed around their periphery to enclose a vacuum gap between the glass sheets.

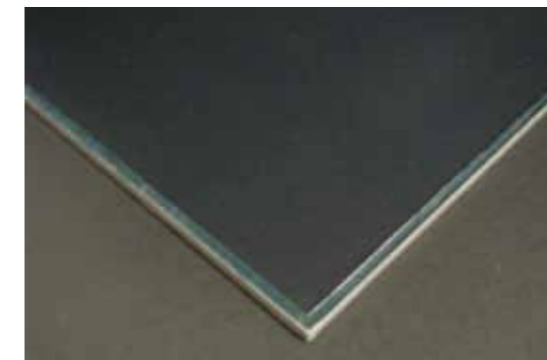


Figure 1: Vacuum glazing

Tiny support pillars are used to separate the glass panes and to prevent them from touching due to atmospheric pressure. Low emittance (low-e) coatings are used on one or more of the internal glass surfaces to reduce radiative heat transfer from the indoor to the outdoor environment through the glazing.

The growth of vacuum glazing technology can only be realised through the development of a cost effective, innovative sealing technique together with a suitable fabrication methodology which has the potential to be implemented effectively at a commercial scale. As part of the CALEBRE project, vacuum glazing was trialled and evaluated in both the laboratory and in the E.ON retrofit test house at Nottingham University.

What we did

The University of Ulster and Loughborough University fabricated a range of vacuum glazings using both a vacuum pump-out technique and a vacuum oven technique.



Figure 2: Vacuum oven and pump-out system

The vacuum oven technique effectively 'seals in' the vacuum, with the glazing being evacuated and sealed within a vacuum oven. The pump-out technique enables the edge sealing process to be completed prior to subsequent evacuation of the glazing through a pump-out hole. As the pump-out system offers some added flexibility in manufacture, this was the technique which was investigated in detail in this project. The development of a modified pump-out arrangement enabled a higher vacuum pressure to be achieved in the glazing during fabrication, thereby improving the thermal performance of the glazing.

The principal attributes of an effective vacuum glazing are the production of a vacuum tight seal and the ability to maintain a high vacuum over the lifetime of the glazing. The parameters investigated which impact on these attributes included the edge seal configuration, edge seal materials and composition, sealing application processes and glass cleaning techniques. At the University of Ulster an indium-based edge seal was further developed together with a modified pump-out system. The optimised process parameters were utilised in the development of a number of vacuum glazings fabricated with two hard coated low-e glass panes (emissivity ~ 0.16).



Figure 3: Fabricated vacuum glazing

The glazings were subsequently laboratory characterised in a guarded hotbox calorimeter and under a solar simulator to assess thermal performance and durability. They were then combined with a third glass pane to form a hybrid vacuum glazing with a vacuum cavity and an air filled cavity.

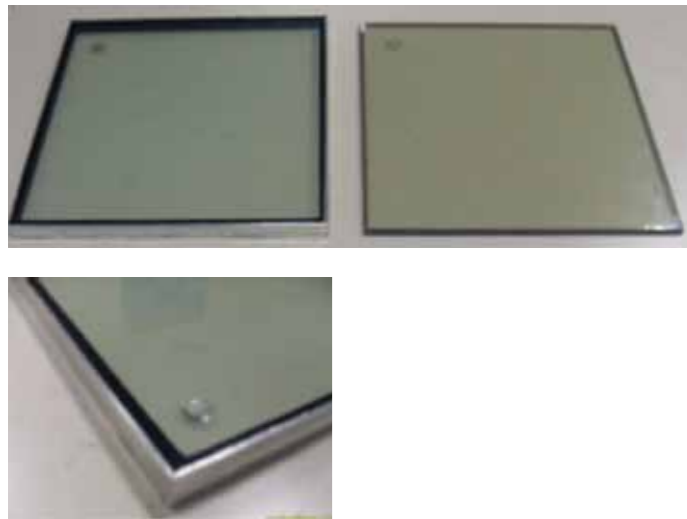


Figure 4: Fabricated vacuum and Hybrid vacuum glazing

The hybrid glazings were installed in one of the bedrooms of the E.ON test house at Nottingham where they were evaluated to determine a range of properties that included acoustic performance, visible/thermal transmission, and impact on indoor thermal comfort. Following this, the glazings were subsequently re-characterised at the University of Ulster to determine if there had been any change in thermal performance during their period of installation at the test house.



Figure 5: Vacuum glazed window in E.ON test house

At Loughborough University a range of new edge seal materials and processes were investigated and trialled with the aim of reducing the cost of the vacuum glazing system. A range of sample vacuum glazings were produced using a metallic alloy not containing indium. Using this new alloy to form an hermetic seal reduces seal material costs by over 50% compared to a seal using Indium. The level of vacuum achieved and outgassing appear satisfactory, however long term durability tests are necessary and are in progress.

What we observed

The vacuum glazings manufactured using the optimised edge sealing parameters and modified pump-out technique achieved centre pane U-values down to $0.85 \text{ Wm}^{-2}\text{K}^{-1}$ for 400 by 400mm glazings employing two low-e coated glass panes (emissivity ~ 0.16). With the addition of a third glass pane and a 12mm air cavity this was reduced to $0.67 \text{ Wm}^{-2}\text{K}^{-1}$ centre pane.

After installation and evaluation in the E.ON test house the U-value of the glazing was measured and was found to have increased to $2.11 \text{ Wm}^{-2}\text{K}^{-1}$. This change in performance may be attributable to the effects of solar radiation, resulting in out-gassing from the internal glass surfaces which in turn leads to a reduction in vacuum pressure and increases thermal transmittance. The introduction of suitable getters will address this issue. Repeat testing of in-situ performance can then take place.

Simulations of the thermal performance of a solid wall dwelling showed that increasing the window area (replacing part of the wall with a window) when using triple vacuum glazing improved the building envelope thermal performance, reducing the winter heat load. Care is, however, required in optimally sizing windows due to the increased solar gains that can occur which can lead to undesired high internal temperatures and building cooling loads.

Conclusions

Work undertaken under the CALEBRE project has shown that high performance vacuum glazing has the potential to greatly reduce heat loss through the building envelope with a consequential reduction in carbon emissions. Practical fabrication of glazings has shown that a centre pane U-value of $0.85 \text{ Wm}^{-2}\text{K}^{-1}$ is achievable using two low-e coated glass panes (emissivity ~ 0.16). By using high performance low-e coatings, for example silver coatings with an emissivity of less than 0.05, this could be further reduced. Simulation results indicate that with an optimised seal design and pillar array, a mid-pane U-value of down to $0.26 \text{ Wm}^{-2}\text{K}^{-1}$ is achievable for triple vacuum glazing.

Recommendations

The CALEBRE project has identified a number of areas where further research is required prior to the commercialisation of this technology. The practical development of a three-pane vacuum glazing is required along with an optimised sealing configuration to reduce heat transfer through the seal and support pillars.

Alternative sealing materials which offer a significant reduction in cost of the glazing need further investigation if commercialisation on a large scale is to be realised. These new seal materials require extensive testing for vacuum integrity, stability and durability both in the laboratory and in-situ under real environmental conditions. Further testing of in-situ window performance for a range of other factors is also required.

Further investigations are required to maintain long term vacuum stability and thus thermal performance of vacuum glazings sealed at low temperature. The use of a low temperature activated getter to sorb any gases released during operation may provide a solution. Alternative cleaning techniques that minimise the adsorption of contaminants on the glass surfaces may also offer potential for prolonging the lifespan of vacuum glazing.

A detailed assessment of the attitude of planners or other statutory control bodies to the wide scale deployment of vacuum glazing is required. This is particularly important for heritage buildings or buildings in conservation areas.

References / Further reading

Anon, 2009, Low-E Insulating Glass for Energy Efficient Buildings, Glass For Europe.

Arya, F., Fang, Y. and Hyde, T., 2012. Fabrication and characterization of triple vacuum glazing at low temperature using an indium-based seal. In: Proceedings of the Energy and Material Research Conference, EMR, Malaga, June 2012. Florida: Brown Walker Press, pp. 521-524.

Fang, Y., Hyde, T. and Hewitt, N. (2011) The Influence of Insulation on the Thermal Performance of Triple Vacuum Glazing. In: Glass Performance Days (GPD) International Conference, Tampere Finland, 4 pp.

Fang, Y., Hyde, T. and Hewitt, N. (2010) Predicted thermal performance of triple vacuum glazing. Solar Energy, 84 (12). pp. 2132-2139.

Fang, Y., Hyde, T. and Hewitt, N. (2010) The influence of emittance of low-emittance coating on the thermal performance of triple vacuum glazing. In: The second IASTED International conference on solar energy. IASTED. 8 pp.

Eames, P.C. (2008) Vacuum glazing: Current performance and future prospects. Vacuum, Volume 82, Issue 7, pp 717-722

Wang, J., Eames, P., Zhao, J., Hyde, T. and Fang, Y. (2007) Stresses in vacuum glazing fabricated at low temperature. Solar Energy Materials and Solar Cells, 91 (4). 290-303.

Zhao, J. F., Eames, P. C., Hyde, T., Fang, Y. and Wang, J. (2007) A modified pump-out technique used for fabrication of low temperature metal sealed vacuum glazing. SOLAR ENERGY, 81 (9), pp. 1072-1077.

Zhao, J., Eames, P., Hyde, T., Fang, Y. and Wang, J. (2006) A new type of In/Cu/In seal for vacuum glazing. In: Renewable energy in maritime island climates conference Dublin 2006. Elsevier. 5 pp.

Hyde, T., Griffiths, P., Eames, P. and Norton, B. (2000) Development of a Novel Low Temperature Edge Seal for Evacuated Glazing. In: World Renewable Energy Congress VI, Brighton, UK. Pergamon. 4 pp.

List of outputs generated by Project CALEBRE to Date

Books and Journal Papers:

Agyenim, F., Hewitt, N. (2010). The development of a finned phase change material (PCM) storage system to take advantage of off-peak electricity tariff for improvement in cost of heat pump operation, *Energy and Buildings*, Volume 42, Issue 9, September 2010, Pages 1552-1560

Banfill, P.F.G., Simpson, S.A., Haines, V.J. and Mallaband, R.A.L. (2012). Energy-led retrofitting of solid wall dwellings – technical and user perspectives on airtightness. *Structural Survey*, 30 (3) 267-279. <https://dspace.lboro.ac.uk/dspace-jspui/handle/2134/11836>

Fang, Yueping, Hyde, Trevor and Hewitt, Neil (2010). Predicted thermal performance of triple vacuum glazing. *Solar Energy*, 84 (12), pp. 2132-2139.

Gillott, M. (2011). Riquilificare o non riquilificare, questo e il problema. In: Davoli, P, ed., *Il recupero energetico ambientale del costruito* Maggioli Editore

Gillott, M., Rodrigues, L., Spataru C. (2010). Low Carbon Housing Design Informed by Research, *Journal of Institution of Civil Engineers*, (Special Issue: Engineering Sustainability) Proceedings of the Institution of Civil Engineers-Engineering Sustainability Vol.163, Issue2, pages 77-87 June 2010.

Gillott, M., Spataru, C. (2009). Best practice in the refurbishment of existing buildings, in Hall, M.R. (Ed.), *Materials for Energy Efficiency & Thermal Comfort in Buildings*, Woodhead Publishing, Cambridge. pp. 649-680

Haines, V.J.A., Mitchell, V.A. and Mallaband, R.A.L. (2012). Merging a practice-orientated approach with an engineering-driven product development: A case study on home improvement. *Journal of Design Research*. Special issue on Design, Sustainability and Behaviour, 10 (1/2) 28-49

Hall, M.R. (Ed.) (2010). *Materials for Energy Efficiency & Thermal Comfort in Buildings*, Woodhead Publishing, Cambridge

Hall, M.R., Allinson D. (2010). Chapter 1: Heat & mass transport processes in building materials, in Hall, M.R. (Ed.), *Materials for Energy Efficiency & Thermal Comfort in Buildings*, Woodhead Publishing, Cambridge

Hall, M.R. (2010) Chapter 14: Hygrothermal materials for heat and moisture control in buildings, in Hall, M.R. (Ed.), *Materials for Energy Efficiency & Thermal Comfort in Buildings*, Woodhead Publishing, Cambridge

Hall, M.R., Tsang, S.C.E., Casey, S.P., Khan, M.A., Yang, H. (2012). Synthesis, characterization and hygrothermal behaviour of mesoporous silica high-performance desiccants for relative humidity buffering in closed environments, *Acta Materialia*, 60(1), January 2012, Pages 89-101.

Hewitt, N.J. (2010). Heat pumps and energy storage – The challenges of implementation, *Applied Energy*, 89(1), p.37-44.

Hewitt, N.J., Huang, M.J., Anderson, M., Quinn, M. (2011). Advanced air source heat pumps for UK and European domestic buildings, *Applied Thermal Engineering*, 31(17-18), p.3713-19

Spataru, C., Gillott, M., Hall, M. (2010). Domestic Energy and Occupancy – A Novel Post-Occupancy Evaluation Study, *International Journal of Low Carbon Technologies*, Vol. 5, pp. 148-157

Spataru, C., Gillott, M. (2010). The Use of Intelligent Systems for Monitoring Energy Use and Occupancy in Existing Homes, Springer Smart Innovation, Systems and Technologies series, ed. Robert J. Howlett and Lakhami C. Jain Heidelberg, 2010

Spataru, C. and Gillott, M. (2011). The Use of Intelligent Systems for Monitoring Energy Use and Occupancy in Existing Homes. In: Howlett, R.J., Jain, L.C. and Lee, S.H. (Eds), *Sustainability in Energy and Buildings*, Springer, 245-254

Spataru, C. and Gillott, M. (2011). The use of intelligent systems for monitoring energy use and occupancy in existing homes. *Intelligent Buildings International*. 3(1), 24-31

Spataru, C. and Gillott, M. (2012). Using a RTL system based on RFID technology for monitoring occupants domestic energy use and behaviour. In: M'Sirdi, N., Namaane, A., Howlett, R.J. and Jain, L.C., (Eds), *Sustainability in Energy and Buildings*. Springer Verlag

Vadodaria, K., Loveday, D.L., and Haines, V., Measured winter and spring-time indoor temperatures in UK homes over the period 1969 to 2010: a review and analysis. *Energy Policy*, accepted July 2013.

Conferences and Seminars:

Arya, F., Fang, Y. and Hyde, T., (2012). Fabrication and characterization of triple vacuum glazing at low temperature using an indium-based seal. In: *Proceedings of the Energy and Material Research Conference, EMR, Malaga, June 2012*. Florida: Brown Walker Press, pp. 521-524.

Banfill, P.F.G., Simpson, S.A., Gillott, M.C., White, J. (2011) Mechanical ventilation and heat recovery for low carbon retrofitting in dwellings, *Proceedings of the World Renewable Energy Congress 2011*, Linköping, Sweden.

Banfill, P.F.G., Simpson, S.A., Gillott, M.C., White, J. (2011) The potential for energy saving in existing solid wall dwellings through mechanical ventilation and heat recovery, *Proceedings of ECEEE 2011 Summer Study on energy efficiency*, France

Banfill, P.F.G., Simpson, S.A., Haines, V.J. and Mallaband, R.A.L. (2011). Energy-led retrofitting of solid wall dwellings – technical and user perspectives on airtightness, COBRA 2011, *Proceedings of RICS Construction and Property Conference*, University of Salford, (Ruddock, L., Chynoweth, P., editors) 430-440.

Burris, A., Mitchell, V., Haines, V.J.A. (2011) An Interdisciplinary Approach to Domestic Comfort, *PRISM Conference*, Gloucester, UK, 19-20 May 2011.

Burris, A., Mitchell, V. and Haines, V.J.A. (2012). Exploring Comfort in the Home: Towards an Interdisciplinary Framework for Domestic Comfort. In: *Proceedings of 7th Windsor Conference (Network for Comfort and Energy Use in Buildings) - The changing context of comfort in an unpredictable world*, Windsor, UK, 12-15 April 2012. 13pp. <https://dspace.lboro.ac.uk/dspace-jspui/handle/2134/11842>

Critoph, R.E., Metcalf, S.J. (2009) Sorption Energy / UW Development of a Domestic Gas-fired Heat Pump, *Heat Powered Cycles Conference 2009*, TU Berlin, 7-9 September 2009.

Fang, Yueping, Hyde, Trevor and Hewitt, Neil (2010). The influence of emittance of low-emittance coating on the thermal performance of triple vacuum glazing. In: *The second IASTED International conference on solar energy*. IASTED. 8 pp.

Fang, Yueping, Hyde, Trevor and Hewitt, Neil (2011) The Influence of Insolation on the Thermal Performance of Triple Vacuum Glazing. In: *Glass Performance Days (GPD) International Conference*, Tampere Finland, 4 pp.

Critoph, R.E. (2010) A 4-bed Carbon-Ammonia Gas-Fired Heat Pump Concept – Technical Overview and Potential for Carbon Reduction, *World Renewable Energy Congress XI*, Abu Dhabi, UAE, 25-30 September 2010.

Critoph, R.E., Metcalf, S.J. (2011) Progress in the development of a carbon-ammonia adsorption gas-fired domestic heat pump, *Proceedings of the Int. Sorption Heat Pump Conference*, Padua, 5-7 April 2011.

Gillott, M., Spataru, C., Hall, M., (2009) Domestic Energy and Occupancy A Novel Post-Occupancy Evaluation Study, *8th International Conference on Sustainable Energy Technologies*, Eurogress, Aachen, Germany, 31 August – 3 September 2009.

Haines, V.J.A. (2010) Invited presentation entitled “A user-centred approach to understanding energy behaviours” containing initial CALEBRE and other project findings. At *Midlands Energy Graduate School event: Social sciences research for a low carbon future*, University of Nottingham, 29 April 2010.

Haines, V.J.A., Mitchell, V.A. AND Mallaband, R.A.L. (2010) Using a Practice-Orientated Approach to Inform the Design of Energy Efficiency Measures for Older Homes. *ERSCP-EMSU Conference*, Delft, 25-28 October 2010. Pages 1-17.

Hewitt, N.J. (2010) Built Environment Energy Storage – The Challenges for Heat Pumps and Air-Conditioning, *World Renewable Energy Congress XI*, Abu Dhabi, UAE, 25-30 September 2010.

Hewitt, N.J. (2010) The necessary development of smart energy networks to maximise renewable energy integration, *9th International Conference on Sustainable Energy Technologies (SET2010)*, Shanghai Jiao Tong University, China, 24-27 August 2010.

Hewitt, N.J. (2010) Heat Pumps and Energy Storage – The Challenges of Implementation, *Sustainable Thermal Energy Management Conference (SusTEM2010)*, Great North Museum, Newcastle upon Tyne, UK, 3 November 2010.

Hewitt, N.J., Critoph, R.E. (2011) The future of efficient heat pumps for home retrofits, *CIBSE Technical Symposium*, 2011, De Montfort University, Leicester, UK, 6-7 September 2011.

Hewitt, N.J., Colclough, S., Huang, M.J., Griffiths, P.W. (2011) High temperature lift retrofit heat pumps for upgrading district heating and seasonal thermal energy stores, *23rd IIR International Congress of Refrigeration*, Prague, 21-26 August 2011.

Hewitt, N.J. (2010) Advanced Air Source Heat Pumps for UK and European Domestic Buildings, *9th International Conference on Sustainable Energy Technologies (SET2010)*, Shanghai Jiao Tong University, China, 24-27 August 2010.

Huang, M.J., Hewitt, N.J. (2011) Prediction of phase change material heat storage for air source heat pump application, *23rd IIR International Congress of Refrigeration*, Prague, 21-26 August 2011.

Kouhestani M., Hewitt, N.J., Huang, M.J. (2011) Exergy analysis of a combined compressor expander heat pump, *23rd IIR International Congress of Refrigeration*, Prague, 21-26 August 2011.

Kouhestani, M., Hewitt, N.J., Huang, M.J. (2011) Developing a combined compressor expander heat pump- experimental evaluation of the compressor and expander, *23rd IIR International Congress of Refrigeration*, Prague, 21-26 August 2011.

Limbachiya, V., Vadodaria, K., Loveday, D. and Haines, V.J.A. (2012). Identifying a suitable method for studying thermal comfort in people's homes. In: *Proceedings of 7th Windsor Conference (Network for Comfort and Energy Use in Buildings) - The changing context of comfort in an unpredictable world*, Windsor, UK, 12-15 April 2012. 15pp. <https://dspace.lboro.ac.uk/dspace-jspui/handle/2134/11845>

Loveday, D., Vadodaria, K., Haines, V., Hewitt, N.J., Hyde, T., Griffiths, P., Critoph, B., Eames, P., Banfill, P.F.G., Gillott, M., Darlington, R., Hall, M., Tsang, E. (2011) Refurbishing the UK's 'hard to treat' dwelling stock: Understanding challenges and constraints – the work of Project CALEBRE, *CIBSE Technical Symposium*, 2011, De Montfort University, Leicester, UK, 6-7 September 2011.

Mallaband, R.A., Haines, V.J.A. and Mitchell, V.A. (2012). Barriers to domestic retrofit – learning from past home improvement experiences. *Retrofit 2012*. University of Salford, 24-26 January 2012.

Mallaband, B., Haines, V. and Mitchell, V. (2013). Exploring Past Home Improvement Experiences to Develop Future Energy Saving Technologies. *Methods for Studying Technology in the Home Workshop, ACM SIGCHI Conference on Human Factors in Computing Systems (CHI)*, Paris, France 27th April – 2nd May 2013

Nagjiew, E., Gillott, M., Wilson, R., (2013). A Qualitative Comparison of Unobtrusive Domestic Occupancy Measurement Technologies. In: Anne Hakansson, Mattias Höjer, Robert J. Howlett, Lakhami C Jain eds. *Sustainability in Energy and Buildings*. Springer Verlag. *Proceedings of the 4th International Conference in Sustainability in Energy and Buildings (SEB '12)*. ISBN: 978-3-642-36644-4 (Print) 978-3-642-36645-1 (Online)

Quinn, M.V., Hewitt, N.J., Smyth, M. (2011) Comparison of the conventional and economised vapour injection refrigeration cycles utilising variable speed capacity control for domestic heat pump retrofit applications, *23rd IIR International Congress of Refrigeration*, Prague, 21-26 August 2011.

Shahn, N., Hewitt, N.J., Huang, M.J. (2011) A review of diesel engine driven heat pumps (DEHPs) and the potential in the UK domestic sector, *23rd IIR International Congress of Refrigeration*, Prague, 21-26 August 2011.

Spataru, C., Gillott, M. (2010) Restoring existing buildings and slowing climate change through a practical case study, *SET Conference 2010*, China, 24-27 August 2010.

Spataru, C., Gillott, M. (2010) Temperature Distribution and Comfort Responses as a Result of Climate Change Impacts on Buildings, *Proceedings of the 3rd International Conference of Passive & Low Energy Cooling for the Built Environment (PALENC 2010) and the 5th European Conference on Energy Performance & Indoor climate in Buildings (EPIC 2010)*, Rhodes, Greece, 29 September – 1 October, 2010.

Spataru, C., Gillott, M., (2010) The Use of Intelligent Systems for Monitoring Energy Use and Occupancy in Existing Homes, *Sustainability in Energy and Buildings 2010 Conference*, Brighton, 5-7 May 2010.

Vadodaria, K., Loveday, D., Haines, V.J.A., Mitchell, V., Mallaband, B., Bayer, S. (2010) UK solid-wall dwellings – thermal comfort, energy efficiency refurbishment and the user perspective – some preliminary analysis from the CALEBRE project, *Proceedings of Conference: Adapting to Change: New Thinking on Comfort*, Cumberland Lodge, Windsor, UK, 9-11 April 2010. London: Network for Comfort and Energy Use in Buildings

Vadodaria, K., Loveday, D., Hodder, S., Gillott, M., Spataru, C. (2010)
Energy efficient retrofit technologies for existing homes and its impact
on thermal comfort – initial findings from the CALEBRE project,
Proceedings of Conference: CLIMA 2010:10th Rehva World Congress –
Sustainable Energy Use in Buildings, Antalya, Turkey, 9-12 May 2010.

CALEBRE in the media:

1. 'Ulster's 'Pamela' Is No Dummy': News release, 12th March 2010, University of Ulster
2. RIBA Sustainable Retrofitting Seminar, Brighton, Dec 2008
3. Green REFURB Symposium, University of Nottingham, Nov 2008
4. ECOBUILD 2009 (Retrofit seminar) & 2010 (CEH seminar)
5. BBC Radio Wales, BBC Radio Nottingham, Trent FM
6. BBC Breakfast
7. BBC News 24
8. BBC NEWS Website
9. ITV Central News
10. BBC East Midlands Today
11. Reuters News Channel