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Refurbishing the UK's 'hard to treat' dwelling stock: Understanding challenges and constraints – the work of Project CALEBRE

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Abstract

Project CALEBRE (Consumer Appealing Low Energy technologies for Building REtrofitting) is a four year £2 million E.ON/RCUK funded project that is investigating technologies and developing solutions for the UK's solid-wall houses to offer energy demand reduction, energy efficient heat generation and energy management combined with user appeal. Understanding how technical solutions can be aligned with householder lifestyles is central to the CALEBRE project. The technologies include: vacuum glazing to achieve exceptionally low U-values whilst being capable of retrofit in existing window frames; advanced gas and electric air source heat pumps that operate at the temperatures needed for integration with existing domestic radiator systems; innovative surface materials for buffering moisture, humidity and temperature; retrofit mechanical ventilation with heat recovery (MVHR) to manage ventilation and its associated heat loss. The technologies are being trialled in facilities that include the University of Nottingham E.ON 2016 House, a highly instrumented replica construction of a 1930s dwelling. Alongside development and trialling, business case modelling of technologies is being conducted to establish mass roll-out strategies, as well as modelling to identify bespoke packages of measures for house refurbishment. This paper introduces Project CALEBRE, its content and scope, and reports some of its initial findings to highlight the challenges and constraints involved in the process of refurbishing the UK's domestic stock.

Keywords Energy Efficiency, Refurbishment, Retrofitting, Domestic buildings, User appeal

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1.0 Introduction- Building refurbishment and UK carbon targets

In response to the increase in greenhouse gas emission and global climate change threats, the UK has set a target of ensuring that the net UK carbon account for the year 2050 is at least 80% lower than the 1990 baseline (1). As part of this process, the recently proposed Fourth Carbon Budget (2), sets out a target to cut Britain's emissions by 50% from 1990 levels by 2025.

In the UK, buildings alone are responsible for up to 40% of carbon emissions, two thirds of which come from the existing housing stock of 25 million dwellings. The majority of this stock will exist in 2050 and is in need of energy efficiency upgrades. Considering this fact, the UK Government has proposed to launch the 'Green Deal' scheme in late 2012, which will offer energy efficiency improvements to homes, community spaces and businesses at no upfront cost to the householder, and recoup payments through savings made by the consumer on the energy bill (2). However, studies have shown that actual savings from the energy efficient retrofitting of existing houses have amounted to less than half of the estimated theoretical savings, partly due to the inability to achieve 100% insulation and partly due to the 'take-back'¹² process initiated due to improvements in thermal comfort (3), (4).

Due to the lack of a cavity, external wall insulation is a favoured approach, however many of the solid wall homes are pre 1930s and are either heritage listed buildings or are located in conservation zones. Hence due to planning and conservation laws, it may not be possible to apply external solid wall insulation to many of the solid wall houses. In addition, for personal aesthetic appeal, householders often choose not to change the exterior of their homes. Furthermore, for technologies like internal solid wall insulation, advanced glazing and heat pumps, information may be needed on consumer appeal due to potential issues relating to the complexity of installation, retention of building character, disruption to householders, perceived benefits, costs and maintenance. For example, ground source heat pumps are not suitable for all properties due to unavailability of ground space or difficult ground geology. Air source heat pumps that are currently available in the market are not suitable to work in conjunction with the existing central heating system, thereby requiring under floor heating to be laid and hence causing significant disruption to homeowners and an increase in refurbishment costs. Also, heat output from such lower-temperature emitters may not adequately heat poorly-insulated traditional constructions. Similarly the application of internal insulation in solid walled properties reduces the thermal mass benefits of temperature and humidity buffering and increases the chances of summertime overheating.

Hence, technologies and solutions are required that not only are easily applicable to existing dwellings but which also take into consideration user appeal and acceptability. An in-depth understanding of the relationship between domestic buildings, retrofit technologies and the human needs of comfort must be gained so that low/zero carbon retrofitted buildings can be achieved that remain acceptable for comfortable occupation. With this in mind, Project CALEBRE (Consumer Appealing Low Energy Technologies for Building RETrofitting) is investigating user-appealing

¹² 'take-back': the process whereby occupants take the benefit of improved thermal efficiency by heating to higher temperatures rather than reducing energy consumption

technologies aimed at reducing the energy consumption of existing houses and their effects on thermal comfort.

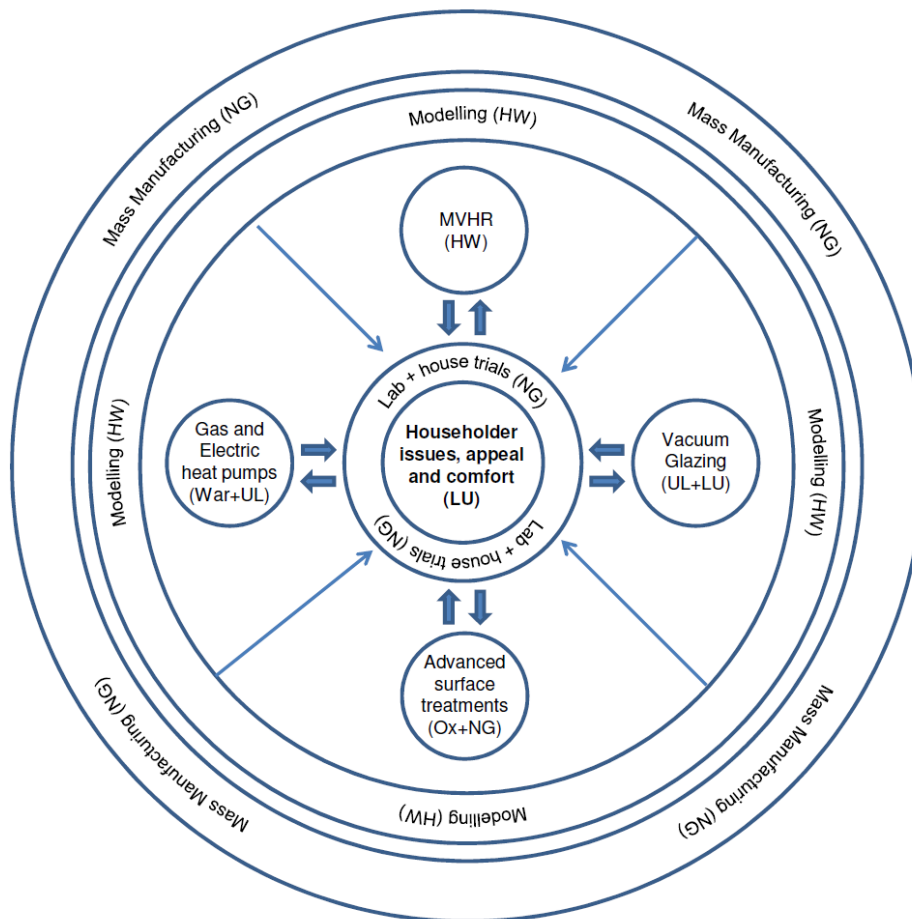
2.0 Project CALEBRE Overview, Content and Scope

CALEBRE is a £2million, four year research project jointly funded by E.ON and RCUK's Energy Programme. The project involves a partnership of six UK Universities: Heriot Watt, Nottingham, Oxford, Ulster, Warwick, and is led by Loughborough. The project takes the approach of identifying, from a householder perspective, the barriers and challenges to the deployment of retrofit carbon-reduction technologies and then, from knowledge gained through householder engagement surveys, appropriately modifies selected technologies for field-trialling, user reaction and thermal comfort evaluation. The selected technologies within the programme cover the range from fundamental to applied research, and include electric and gas-fired heat pumps, mechanical ventilation heat recovery (MVHR), vacuum glazing and innovative advanced surface treatments to control temperature and moisture via nano-technology. These technologies are being developed within the laboratory and most will be trialled in test houses for evaluation of their installation processes, performance, energy efficiency and thermal comfort. The E.ON 2016 house is one such test site built at the University of Nottingham and a replica of a typical 1930s UK dwelling. Model development to support selection of bespoke packages of refurbishment measures is being pursued, together with mechanisms necessary for mass market roll out of technical solutions..

This paper presents an outline of the key components of the CALEBRE project, together with a summary of progress to date and some of its preliminary findings. These relate to the householder survey, the development of the heat pumps and advanced glazing, and the trials at the test house on the performance of the MVHR system in relation to progressive sealing upgrades.

3.0 Project Components and Research Teams

Figure 1 illustrates the key components of Project CALEBRE and the teams leading those elements of the programme. Overall leadership and management of the project is provided by Loughborough University (Department of Civil & Building Engineering).



Key to figure:

HW = Heriot-Watt University
 NG = University of Nottingham
 Ox = Oxford University

War = Warwick University
 UL = University of Ulster
 LU = Loughborough University

Figure 1: Project CALEBRE, its elements and teams

An outline of each element, the team responsible for the work, and the linkage to other parts of the project is provided below.

3.1 User Dimensions: householder surveys

One of the most significant challenge facing the deployment of any new technology is its appeal to, acceptability by, and interaction with domestic users. Unless these aspects are fully accounted for in the further development of candidate technologies, their uptake and impact will, at best, be limited. No single solution or intervention is capable of delivering the substantial reductions necessary on a national scale and required within an individual property. Instead, a combination of measures is needed. This requires an understanding of the processes, trigger-points and timescales of home improvements, together with the motivations and barriers faced by home owners in refurbishing their properties. It also requires an understanding of home owners' lifestyle choices, routines and comfort criteria to ensure that energy efficiency solutions and technologies being developed are acceptable and appealing to them. With a view to develop this understanding, CALEBRE has taken a practice orientated User Centred Design (UCD) approach (5) to carry out an in-depth qualitative survey of householders' attitudes towards home refurbishments and

energy efficient technologies. This part of the project is being led by a team of researchers at Loughborough University's Design School and informs the technology and model development aspects of the project, as well as providing householder feedback about the technical solutions.

3.2 Energy Supply Technologies: electric and gas heat pumps

To date, the application of heat pumps in the UK has been largely limited to new build properties involving mainly ground source heat pumps coupled with under-floor heating. Currently, heating in the vast majority of the UK's 24 million dwellings is provided through gas centrally-heated wet radiator systems which require the supply of hot water at temperatures above 60°C. The performance and efficiency of heat pumps significantly reduces at such high temperatures, whilst the ability of a wet radiator system to provide adequate heating deteriorates significantly when the temperature of hot water supply is lower than 60°C (6). Furthermore, ground source heat pumps either require significant ground space if using horizontal collectors, or are expensive if using vertical collectors. Considering these issues, CALEBRE is currently developing and testing air source heat pumps that:

- a) are easy to retrofit with existing wet radiator systems to efficiently supply hot water at or above 60°C
- b) use air as the low grade heat source, thereby not requiring large areas of ground, and instead addressing problems of defrost related to air coils
- c) are low noise, affordable and cost-effective

The team at the University of Ulster is leading the work on electric heat pumps, involving a combined compressor/expander heat pump where the higher pressure/temperature regime provides efficiency gains by utilising a turbine to recover expansion energy.

A gas fired air source heat pump is also being developed as part of the project by the team at Warwick University. This is seen as a transition technology, as presently the national electricity grid low voltage local area network may not be able to sustain a UK wide switch to all-electric air source heat pumps. In addition, the gas network is already in place in most areas of the UK, to meet consumer requirements of this transition technology. The design of this gas fired heat pump (patent pending) is in advance of current German developments (7). Both heat pumps will be tested in the laboratory and the electric heat pump will be trialled in a test house, and findings will inform model development aspects of the Project.

3.2 Energy Demand Technologies: vacuum glazing, and surface treatments

The thermal performance of the untreated envelope of solid wall dwellings is generally very poor with significant heat loss through walls and windows. If conventional single and double glazing can be replaced with high performance vacuum glazing, then a significant improvement in thermal performance could be achieved. It may also be possible to increase window to wall area ratios whilst improving total building envelope thermal performance and natural lighting. Research teams at Ulster and Loughborough Universities are developing and triple vacuum glazing with target U-values down to $0.33 \text{ Wm}^{-2}\text{K}^{-1}$ and with cheaper, better edge seals. This glazing is being fabricated using annealed glass and a range of low-e

coatings and its characterisation is being undertaken using a guarded hotbox calorimeter and a solar simulator at the University of Ulster.

The application of this advanced glazing system on its own, or together with wall insulation, can help reduce heat losses considerably. However, if internal insulation is used (as might be preferred in conservation areas), then this produces another challenge- that of temperature and humidity buffering. Buildings that are well-insulated internally and have low air leakage become very sensitive to changes in thermal energy loads and humidity loads (8). This is a particular problem when internal insulation is installed, thus isolating masonry or timber materials which normally act to partly buffer air temperature and relative humidity fluctuations by sorption/desorption of heat and moisture.. To overcome this challenge, a combined team at the Universities of Nottingham and Oxford is attempting to synthesise a suitable nanocomposite material for air temperature and relative humidity buffering. Characterisation of desiccant properties has been conducted, a prototype composite (mesoporous desiccant-inorganic PCM) will be produced and its behaviour will be validated at a macro-scale through laboratory testing.

3.3 Energy Control Technology: MVHR system

Another significant challenge to be addressed in the retrofit of existing dwellings is managing ventilation and infiltration. Heat losses from ventilation and infiltration in existing dwellings are a significant channel of energy waste. Mechanical ventilation and heat recovery has the potential to save energy in solid wall dwellings as well as to satisfy sustainability metrics associated with indoor air quality and health.

The benefits possible from using a mechanical ventilation heat recovery (MVHR) system cannot be achieved if there is significant extraneous air leakage and consequent heat loss, so these must be addressed prior to installation of an MVHR system. The Project is investigating this relationship, and has installed, monitored and modelled the performance of a retrofitted MVHR system relative to different levels of air tightness. This is being led by Heriot Watt and Nottingham Universities, and emerging results are reported in section 4.

3.4 Test House Trialling, Evaluation and Thermal Comfort

As technologies emerge from development and laboratory testing, they will undergo in-situ trialling in test houses. The E.ON 2016 House is a re-construction of a typical 1930s UK dwelling, and is part of the Creative Energy Dwellings work at Nottingham University (Figure 2). The house is occupied, and is extensively equipped with sensors for monitoring of its internal and external environment, and was upgraded at the start of Project CALEBRE to allow individual tracking of occupants combined with identification of their personal carbon 'signatures' through their use of utilities and appliances. This is achieved through the use of a Real-Time Location System (RTLS) system based on ultra wideband (UWB) radio frequency (RF) technology. To date, tests have been conducted on the retrofitted MVHR system, alongside progressive sealing upgrades. This will be followed by installation and trialling of a window fitted with vacuum glazing, with heat pumps trials being conducted in other locations. In all cases, the technologies will be evaluated for performance, energy efficiency, and their impact on thermal comfort, as well as issues related to retrofit practicalities. Thermal comfort evaluation is made using heated manikins (Figure 3) to provide an objective measure of heat transfer between a human occupant and their environment.

House trials are led by a team at Nottingham University, with thermal comfort evaluation by Loughborough and Ulster Universities, plus the relevant teams responsible for particular technologies.



Figure 2: The University of Nottingham E.ON 2016 test house which is being used for trialling of CALEBRE technologies



Figure 3: Heated thermal manikin 'Victoria' being used at the test house for thermal comfort trials

3.5 Mass Manufacture and Roll-Out

Refurbishment of the UK's existing housing stock (of which more than 8 million are solid-wall properties) is a challenge of huge proportions, yet must be an essential component of a national strategy for achieving the aspiration of an 80% carbon reduction by 2050. In relation to such a mass refurbishment programme, this Nottingham-led component of the CALEBRE programme sets out to ensure that the next generation of energy saving technologies are successfully implemented into high quality and long lasting products at an affordable cost to consumers. Making the transition from the technology prototypes being researched and developed within the project into customisable, user-specific solutions will require support through product design, cost-efficient volume manufacture, maintenance, and cost effective retrofitting into existing homes. In this work package, key product features will be linked to function and ease of manufacture to develop an integrated design and manufacturing methodology that will be verified and demonstrated for the cases of heat pumps and vacuum glazing technologies developed in CALEBRE.

3.6 Model Development

Two key barriers to the uptake of technological interventions designed to reduce energy and CO₂ emissions of dwellings are (a) clarity of information and (b) transactional exhaustion. Unclear information presented to the householder could result in wrong choices being made, which in turn results in a series of transactions with installers and others as mistakes are rectified. What is needed is a single computational tool able to inform the householder of the package of measures needed for their home for achieving the required energy and CO₂ reduction, and for

this to contribute to a 'one-stop-shop' approach to the challenge of large-scale domestic refurbishment.

Starting with the computational tool developed by the TARBASE project (9), the aim within Project CALEBRE is to undertake its further development to produce a desktop-based, computational tool that will take information about the dwelling, occupancy and location and output a tailored system package that will achieve the emissions reductions. The new version will take into account the user perspectives as well as performance data about the technologies established from the laboratory tests and field trials. To date, this model now includes glazing, insulation, air tightness, occupancy, lighting, small power consumption, deployment of renewable energy generation and boiler replacement technologies. The data from the test houses is contributing to the verification of this tool, in particular, the relationship of air tightness with the operation of mechanical ventilation with heat recovery (MVHR). The model has also been used to better understand the effects of order of retrofit of energy-saving technologies in domestic dwellings. This part of Project CALEBRE is being led by the team at Heriot Watt University.

4. Summary of Selected Results, and Progress to Date

4.1 Householder survey

In-depth qualitative surveys were conducted in 20 households (incorporating 66 permanent occupants) exploring past home renovation work and attitudes to new energy-saving technologies. Emerging 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, ongoing 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 like single glazed 'character' windows, for example, 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 time that would be taken to carry out works, with unknown professionals generally not being given work. Table 1 summarise key findings from the user survey work to date. A more extensive householder survey is being planned during the next stage of this project.

Table 1: Summary of key findings from the user survey work to date

Motivation, timing, cost	Special considerations
Saving energy not a priority...need to repair, or desire for comfort, drive most improvements	There is a desire to maintain & restore 'original' features
Most major work done at purchase, with ongoing improvements at intervals	Windows are important 'character' features to householders – some retaining single-glazed, draughty windows in preference to modern PVC ones
Cost often prevents work being done, or done 'in keeping' with age of property	Lack of knowledge of professionals on how to deal with solid wall properties and their character features may be an issue
Refurbishment process	Trust Issues
Most householders complete improvements piecemeal	Few householders would accept unknown professionals
Bulk of work done before moving in, enough to achieve occupation	Professionals chosen on price, trust, recommendation, & time known
Few prepared to move out for a refurb, unless health issues	Same trusted professional used for variety of jobs, in preference to lesser known specialists
Most 'lived in' during improvements, using other rooms	Many householders do improvements themselves

4.2 Heat Pumps and Vacuum Glazing developments

The electric heat pump modified to operate more efficiently at higher output temperatures has been initially tested in the laboratory. Initial results show COPs in the region of three, with further tests planned in a controlled environmental chamber, followed by trials in a test house on the campus of University of Ulster. The prototype of the gas fired heat pump is physically complete and is shown in Figure 4. Instrumentation and control electronics have been installed and commissioning in the environmental chamber at Warwick University is underway.

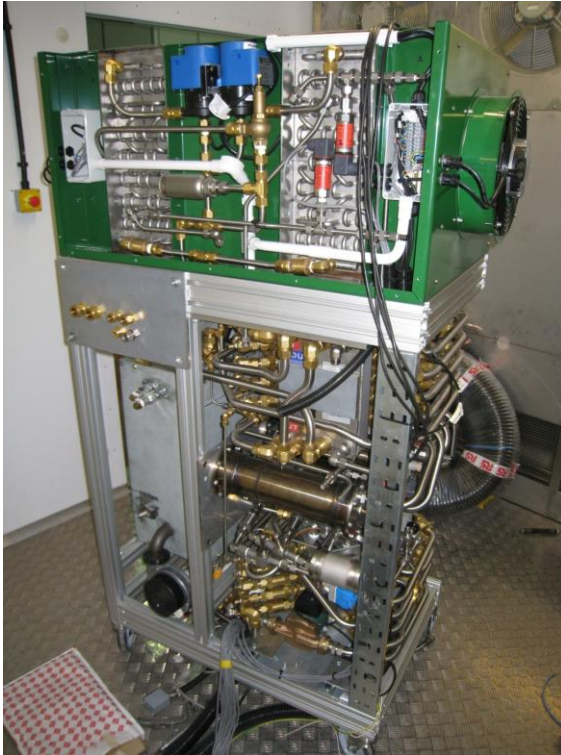


Figure 4: Prototype gas-fired heat pump, February 2011.

A key challenge with vacuum glazing (Figure 5) is the edge sealing and consequent longevity of the vacuum. A new, less expensive, edge seal has been devised for manufacturing and testing of 'double vacuum glazing' (two glass panes separated by one vacuum). Results from initial thermal characterisation tests of a section of fabricated double vacuum glazing (400mm by 400mm) has given a U-value of $1.26 \text{ Wm}^{-2}\text{K}^{-1}$. Thermal modelling has been carried out to predict the performance of a triple vacuum glazing system (three glass panes separated by two vacuums) and this has indicated a potential to achieve a U-value down to $0.26 \text{ Wm}^{-2}\text{K}^{-1}$. Work is progressing to install and test a double vacuum-glazed window in the E.ON 2016 house at Nottingham University and to trial its performance in a range of practical situations.

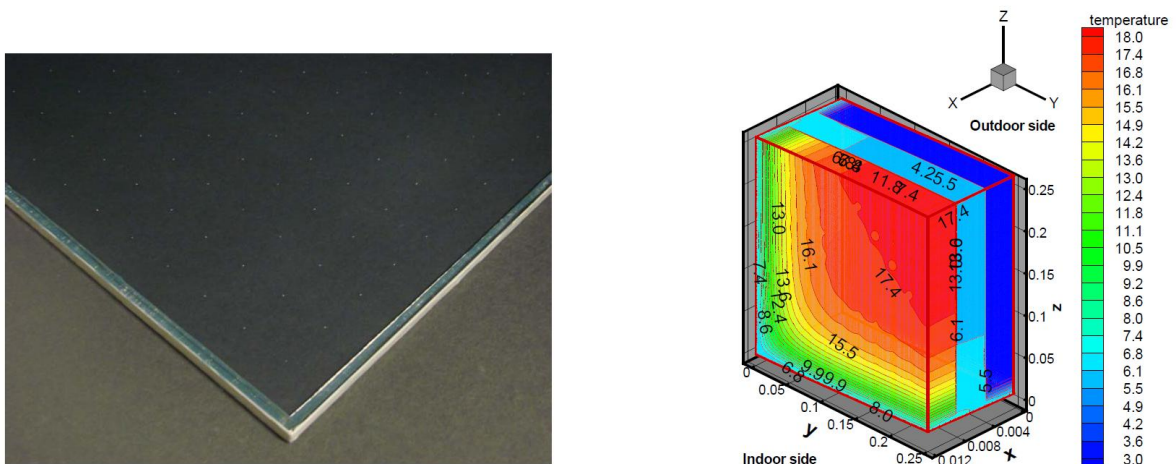


Figure 5: View of low temperature sealed vacuum glazing and predicted temperature profiles.

4.3 MVHR and sealing upgrade

MVHR systems operate by controlling ventilation through a building and recovering heat from the extract. To work effectively, there is a requirement for the building to be sufficiently airtight. Existing domestic buildings are generally fairly 'leaky', so installing an MVHR system alone will not suffice unless accompanied by suitable air-tightness measures. To investigate the level of air-tightness required, the CALEBRE Project retrofitted an MVHR system into the E.ON 2016 test house, and evaluated its performance relative to successive sealing upgrades to the house. Air tightness levels at the test house were improved in four successive stages from a base case of 15.57 m³/m²/hr @ 50pa, to 14.31, 9.84, 8.6 and finally 5.0 m³/m²/hr @50pa as shown in and the following results were obtained.

Table 2: Successive sealing upgrades at the test house

Stage of improvement	Air tightness achieved	Measures taken
Base case	15.57 m ³ /m ² /h @50pa	Single glazed windows, uninsulated walls, floor and roof space, no draught proofing
Stage 1	14.31 m ³ /m ² /h @50pa	Double glazing installed, insulation applied to walls and loft, draught-proofing applied to windows (excluding kitchen, bathroom and WC) and doors, installation of whole house MVHR system
Stage 2	9.84 m ³ /m ² /h @50pa	Kitchen, bathroom, WC windows and undercroft trap-door draught-proofed. Draught-proofing throughout the house redone to address inadequate installation in Stage 1.
Stage 3	8.6 m ³ /m ² /h @50pa	Window trickle vents blocked up, service risers sealed, pipework envelope penetrations sealed (radiators, water pipes etc.), sealing around boiler flue, covers fitted to door locks, kitchen fan removed and bricked up.
Stage 4	5.0 m ³ /m ² /h @50pa	Ground floor insulated and sealed

Table 2 illustrates that the retrofit sealing of a typical domestic house is a challenging task, requiring quality workmanship and attention to detail. This also applies to the retrofit installation of the MVHR system itself. The system was installed by a commercial company, but was found to be unbalanced with over-pressurisation of the house leading to increased exfiltration. Measurements showed that when the MVHR system components are specified to best practice standards, the test house was able to achieve an overall reduction in energy consumption at the air permeability of 5 m³/m²/h @50pa (equivalent to an estimated 4.8 ach⁻¹). However, to achieve this level of air-tightness in existing houses might require a Stage 4 upgrade. This would entail both significant disturbance to occupants and cost. On a cautionary note, however, one should also be mindful of possible risks incurred by moisture build-up within fabric elements as a result of increased air-tightness – more research is required on these issues.

5. Conclusions

An introduction to Project CALEBRE, its content, scope, approach, user dimensions, technologies, and progress have been reported, and some details of selected findings to date have been presented.

Householder surveys have provided insights into why and how people make improvements to their homes, together with their attitudes, motivations and barriers when it comes to energy efficiency refurbishment. Opinions on energy saving technologies and user appeal have been gathered which have helped to inform the on-going design and development of CALEBRE technologies.

Gas and electric air source heat pump prototypes that are specifically designed for retrofitting have been developed. Results from laboratory tests have been encouraging, and house trials are now planned. Work on the fabrication of double vacuum glazing has demonstrated that creating a robust edge seal is one of the biggest challenges. The modelling work suggests that exceptionally low U-values can be achieved through triple vacuum glazing.

The monitoring work on the MVHR system and sealing upgrades has identified the challenges involved and conditions of best use. Attention to detail and quality of workmanship are key to achieving the desired levels of air tightness and consequent performance of the MVHR system. Air tightness levels in the region of $5 \text{ m}^3/\text{m}^2/\text{h}$ @50pa (4.77 ach^{-1}) or lower appear to be desirable for effective energy saving from a retrofit MVHR system.

The work of CALEBRE is ongoing and further findings will be disseminated through appropriate means, including journal papers, conferences and seminar proceedings, as well as on the project website (www.calebre.org.uk)

Acknowledgements

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