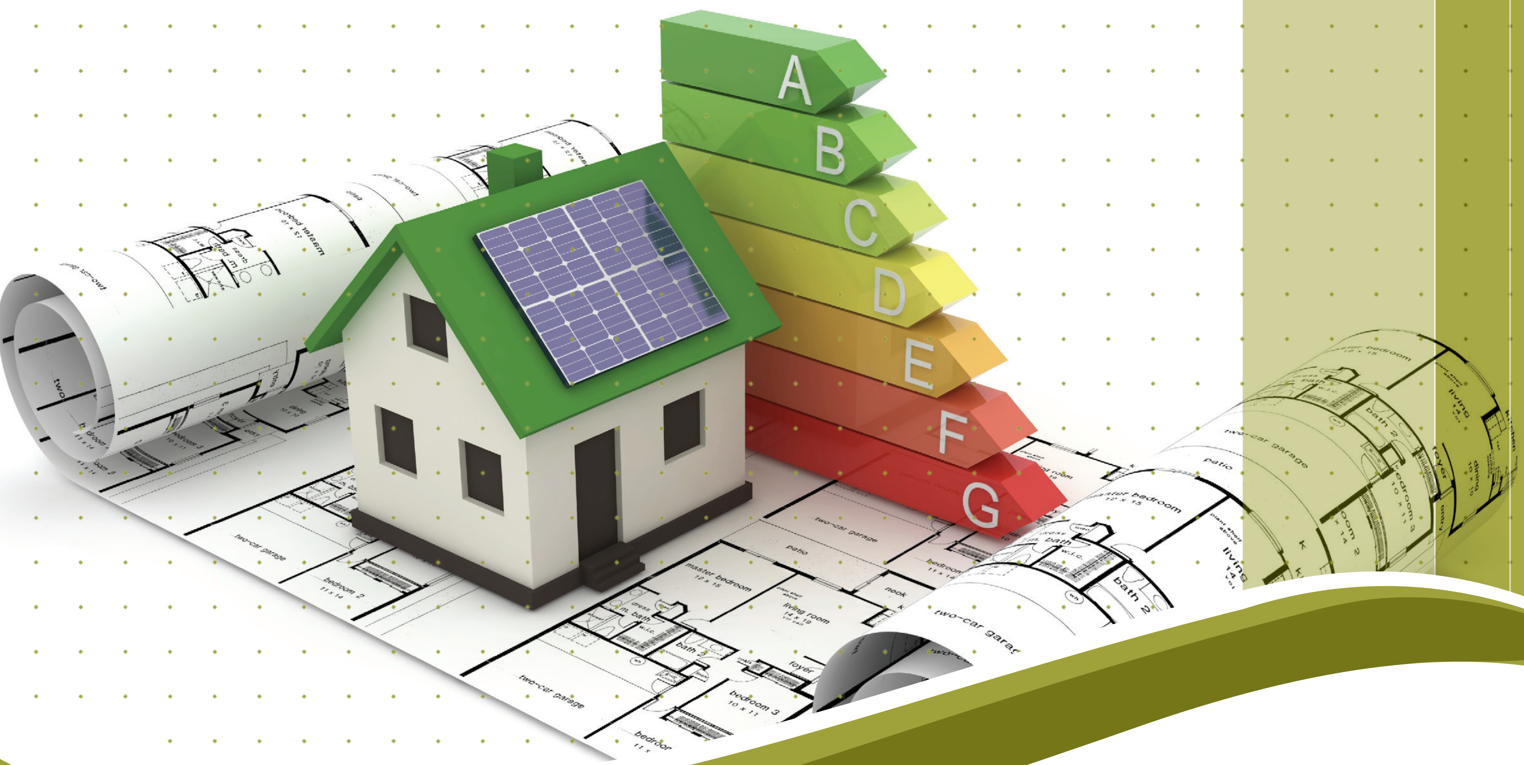
LOW CARBON DOMESTIC RETROFIT

Retrofit insights: perspectives for an emerging industry

Key Findings: Analysis of a selection of Retrofit for the Future projects



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Driving Innovation

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1. Introduction

Retrofitting buildings is one of the biggest opportunities for jobs and growth in the UK, but to make such large-scale changes, a significant transformation in the industry is needed. To help address the UK's national target to reduce carbon dioxide emissions by 80%, compared with 1990 levels, by 2050 and to support a step change in the built environment industry, it is important to record and share learning from an analysis of real-life projects.

Between May 2011 and July 2012, the UCL Energy Institute (UCL-Energy), working in partnership with the Institute for Sustainability, undertook a post-occupancy evaluation study on a sample of the projects funded by the Technology Strategy Board's Retrofit for the Future (Rt4F) programme in London.[1] The core aim of the programme was to reduce the carbon emissions of existing homes by a minimum of 80% (TSB 2009) while providing affordable warmth for the occupants.

1.1 Research aims and objectives

The intention of this report is to use learning and insights from this analysis to help small and medium-sized enterprises (SMEs) in the construction industry to prepare for emerging business opportunities in retrofit. As a result, the UCL-Energy team had the following research objectives:

1. To understand the retrofit strategies adopted by the Project Teams (PTs) by carrying out hindsight reviews and "wash-up" meetings
2. To capture the occupants' experiences of the retrofit process and their response to the outcomes
3. To investigate the physical outcomes of retrofit interventions by analysing physical monitoring data
4. To identify and understand the factors and mechanisms that affect outcomes, by carrying out an integrated analysis of all the above data.

Insights from hindsight/"wash-up" meetings and post-occupancy interviews have been separately reported (Raslan et al. 2012; Chiu et al. 2012). This report presents an analysis of the overall findings from each of these elements.

1.2 Sampling strategy

The UCL-Energy team has used a multi-case study design (Gray 2004) to investigate the strategies, mechanisms and processes that influence the outcomes of low energy retrofit in social housing. The case study approach, working with a small number of cases, allows the uniqueness of each individual case to be explored (Patton 2002). Maximum variation sampling allows key issues that cut across cases to emerge out of the heterogeneity. The study design turns the apparent weakness of a small sample into a strength.

Eight projects (comprising ten houses) were selected from the 25 London projects funded by the R4tF programme. House types selected included semi-detached, detached and terraced properties built between the late 19th and late 20th centuries. Households were selected for social and economic diversity.

[1] The R4tF competition offered partnerships, working with or led by a social landlord, £150,000 to retrofit, and subsequently monitor for two years, a social housing street property, with the aim of achieving a minimum 80% reduction in associated CO_2 emissions.

Because of the priority given to the variety of house types, households and sites in the sampling strategy, the sampling of the PTs was coincidental and secondary. Despite this, the PTs in the sample also differ significantly in structure, composition and prior retrofit experience.

The key characteristics of the sample of ten R4tF projects are set out in Table 2.1. All of the PTs consisted of a social landlord, an architect, mechanical and electrical consultants, energy and other consultants, and contractors except case F, where an architect was not involved. In most cases, the social landlord acted as the project lead, and often there was a specific liaison person assigned by the social landlord to liaise between the PT and the occupants (e.g. Cases D and B1–B3).

Overview

The R4tF sample reveals a host of complex issues. Sections 3.1–3.3 discuss the main issues, and Section 3.4 relates them to choices made by PTs and the constraints that they had to negotiate. Section 4 provides some insights into the emergent practices of the industry in response to this complexity. Section 5 describes how the occupants adapted to these complex systems and describes the key role of engagement, communication and information in supporting interactions between systems, occupants and PTs. Although physical monitoring data for the sample of R4tF projects used for this analysis are limited, there are enough to present an overview of the outcomes of the retrofits (Section 6) and to support an economic analysis (Section 7). Finally, Section 8 presents insights on policy and practice, and on the potential for business development in the light of the findings.

Typical Victorian terrace homes in London

A combination of focus groups, post-occupancy interviews and individual interviews was used to understand the perspectives of the different participants in the projects. Unfortunately, at the time of writing, monitoring data (internal temperatures and energy data) for only four cases were available, and the analysis was therefore restricted.

The analysis started by capturing actors' experiences and then corroborating these against physical observations and monitoring data. This made it possible to build up a detailed understanding of the retrofit strategy, the process of implementation and occupants' resulting experiences in each case. A cross-case comparison was then carried out to identify patterns of social and other systemic constraints that appeared to have a bearing on outcomes.

Cases	B1	B2	B3	F	G	E	C	H	D	A
Team structure	HA-led			LA-led	LA-led	HA-led	LA/HA-led	Architect-led	Architect-led	Architect-led
House type	1970s terrace			1960s semi-detached	Edwardian end of terrace	Victorian mid-terrace	Victorian end of terrace	Inter-war detached	1960s mid-terrace	1990s mid-terrace
Composition of household	Family of 4	Family of 4	Family of 3	Family of 7	BME family of 5	Single man	Elderly woman	Elderly couple	BME family of 8	Single mother, 2 children
Stated retrofit approach	Fabric first			Insulate then generate	Fabric first	Modified Passivhaus	Fabric first	Passivhaus	Passivhaus	Whole house
Summary of fabric and ventilation strategies	EWI, AC, CHS, low leakage, whole house MVHR			HPCF, PIV	EWI, low leakage	HWI MEV+HP, inter-mediate leakage	HWI	EWI, AC, low leakage, whole house MVHR	EWI, AC, low leakage, whole house MVHR	HWI, inter-mediate leakage, HV (natural + individual MVHR)

In order of increasing satisfaction and PT integration

Table 2.1: Key characteristics of the ten R4tF retrofit projects

Notes: The order of cases in this table corresponds roughly to the rank order of satisfaction and to the degree of integration within the PTs, both increasing from left to right. The three Case B houses were part of a terrace of four, the whole of which was retrofitted as part of an R4tF project. The UCL-Energy team was only able to make contact with the occupants of three of these.

Key:
AC = airtight construction
BME = black and minority ethnic
CHS = communal heating system
EV+ HPHR = exhaust ventilation with heat pump heat recovery
EWI = external wall insulation
HA = housing association
HPCF = high performance cavity fill
HV = hybrid ventilation
HWI = hybrid wall insulation – e.g. external at the back, internal at the front
LA = local authority
MVHR = mechanical ventilation heat recovery
PIV = positive input ventilation

3. System complexity

Retrofit in the construction industry is all too often seen as the application of a collection of novel engineering systems rather than as a social–technical system in which human behaviour and organisational structure and culture play a crucial part. While dwellings and their energy systems are physical systems, they are not independent of social and organisational behaviour. The interactions between the different components (heating and ventilation systems, solar thermal etc) and the physical envelope of the dwelling, and with the people who retrofit and inhabit it, form a complex system whose behaviours cannot always be predicted, particularly during times of rapid change.

3.1 Approaches to retrofit

The labels adopted by PTs to describe their approaches are set out in Table 2.1. A superficial comparison of these labels reveals a high degree of similarity, but this is misleading. Efforts to reduce fabric and ventilation heat losses were common themes in all retrofits, but there was significant variation between projects target air tightness varied by a factor of five. Though all the projects used gas as the main form of heating, complemented by solar water heating and in one case by an exhaust air heat pump, ventilation strategies varied widely. Complementing the variations in fabric and engineering, there were significant differences in the way PTs approached the occupants and the particular design possibilities offered by each dwelling.

The strategy which stands out most is Passivhaus. This is not because it is necessarily the most appropriate strategy for large-scale retrofit in the UK, but because of its tight performance specification and the organisational and scientific backing that its proponents receive from the Passivhaus Institut, its UK affiliate the Passivhaus Trust, and the international Passivhaus community.

3.1.1 Deep versus shallow retrofit

Deep and shallow retrofit are qualitatively different. While shallow retrofit can be achieved by insulation, deep retrofit characteristic of the R4tF sample typically also requires replacement of existing heating and ventilating systems, and the installation of renewables. This is because of the proportions of energy used for space heating, water heating and lights and appliances in typical UK homes. Gas accounts for roughly 60% of the CO_2 emissions of a typical UK house (somewhat more in hard-to-heat houses), with the rest made up by electricity for lights and appliances.

Assuming that the retrofitted house continues to use gas for space and water heating, up to half the gas can be saved by insulating the fabric and hot water system. Perhaps a third of the electricity can be saved by changing the lights and appliances. Achieving CO_2 savings much above 50% requires either systems such as photovoltaics to offset the emissions from the gas and electricity, or a switch to low carbon heat, for example from combined heat and power.

3.2 Fabric strategies

Although fabric insulation was a feature of all the dwellings, the different PTs took very different approaches to the balance of risk, costs and reduction in heat loss, based on their assessments of opportunities and constraints in each dwelling, and the different attitudes of and to occupants. Cases D and H adopted a fully fledged Passivhaus strategy, involving the reduction of wall U values to around 0.14, and roof U values to around 0.08 W/m^{2}K. The PT leader's original aim was to reduce air permeability to below 1 ac/h @ 50 Pa, by the addition of a continuous air barrier around the whole dwelling.[2] This target was missed at both houses, but the final figures – 1.9 and 1.7 ac/h @ 50 Pa – are remarkably low compared with the average for existing dwellings in the UK, which is around 12 ac/h @ 50 Pa (Stephen 2000). Moreover, they are low enough for the chosen ventilation strategy – whole house mechanical ventilation with heat recovery (MVHR) – to provide significant CO_2 savings.

Cases A, C, G and E took a different approach to the fabric, accepting somewhat higher U values and significantly higher target air leakage rates – e.g. 5 ac/h @ 50 Pa – and avoiding the use of whole house MVHR.

The dwellings in the UCL-Energy team sample span a wide range of types and ages, and the detailed approaches to fabric insulation are similarly varied. Cases B, D, G and H had no clear heritage value and were simple in form. In their original pre-retrofit state, the walls of Cases G and H were part or fully rendered. There were therefore no aesthetic or practical obstacles to external insulation, and PTs took full advantage of this, adding up to 250 mm of external insulation.

External insulation:

- minimises impacts on occupants
- enables thick and therefore relatively cheap insulants to be used, while achieving low U values
- minimises risks to existing walls from interstitial condensation
- requires careful coordination at junctions with the roof and with drainage
- should be done at the same time as the replacement of windows and external doors, in order to minimise thermal bridging.

Other PTs adopted a hybrid insulation strategy – typically external at the rear, and internal on facades that would be visible from the front (Cases A and E).

[2] Air permeability can be quoted both in air changes per hour (ac/h) and m^3/m^2/h, at a test pressure difference of 50 Pa. In most situations, there is little difference between the two: 1 ac/h ≈ 1 m^3/m^2/h at 50 Pa.

3.3 Ventilation strategies – choices and consequences

The role of heating and ventilation systems is second only to that of the fabric in retrofit performance. Successful retrofits require an understanding of the ways in which these systems interact with the building fabric, control systems and occupants.

3.3.1 Air tightness and ventilation strategy

Ventilation strategies used in the UCL-Energy sample are shown in Table 2.1. Six out of the ten projects (Cases B, D, G and H) adopted whole house MVHR, Case E adopted a continuous mechanically assisted passive stack system, Case F adopted positive input ventilation, and Cases A and C adopted hybrids of mechanical and natural ventilation. Data from the "wash-up" meetings suggest the key drivers were:

- decisions on the likely level of air tightness that could be achieved in each case
- assessments of occupants' needs
- judgements on the comparative costs and risks associated with the installation of ductwork in existing dwellings.

Most PTs were aware that MVHR saves significant amounts of energy only in airtight dwellings – the principles are illustrated qualitatively in Figure 3.1. This shows that there is likely to be little to choose between continuous mechanical extract systems and MVHR at air permeabilities around 5 ac/h, but that once this threshold is crossed, well-designed, installed and commissioned MVHRs allow steadily increasing energy benefits from air tightness.

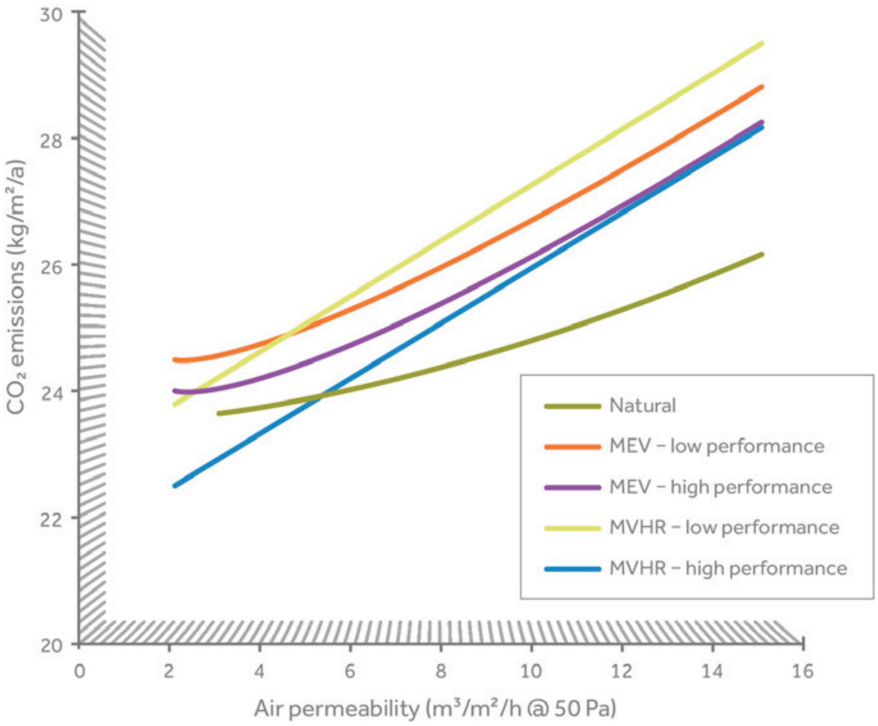


Figure 3.1: Impact of air leakage on CO_2 emissions for three ventilation strategies[3]

[3] There are a number of important differences between the systems that are not captured in this graph. Heat recovery is normally associated with MVHR, but other options exist. The PT for Case E chose to add heat recovery to a mechanically assisted passive stack ventilation system. This used the outgoing air as the heat source for a heat pump which (in parallel with a solar thermal system) pre-heated the water supply to a gas-fired combi boiler. In practice, at current energy prices, this combination offers only modest cost savings.

The Case E occupant found it impossible to understand the system. This was compounded by protracted problems in commissioning. Though he had been very supportive throughout, the resident was understandably frustrated by the lengthy process. The designers asked him to turn the system off until the commissioning had been fully resolved.

Energy systems in the domestic setting need to be inherently robust, and easy to understand by untrained residents. While a simple system meets both these needs, the drive for innovation inevitably leads to complexity. For a complex system to function in a domestic environment, it must have simple user controls and it must have been thoroughly tested before installation. Further to this, it must either be installed by an expert in that system (which may be costly and impractical), or it must be capable of being installed by an electrician/plumber with no specialist training. To produce a product of this type requires sustained investment by manufacturers, which in turn requires a clear and consistent policy framework from government.

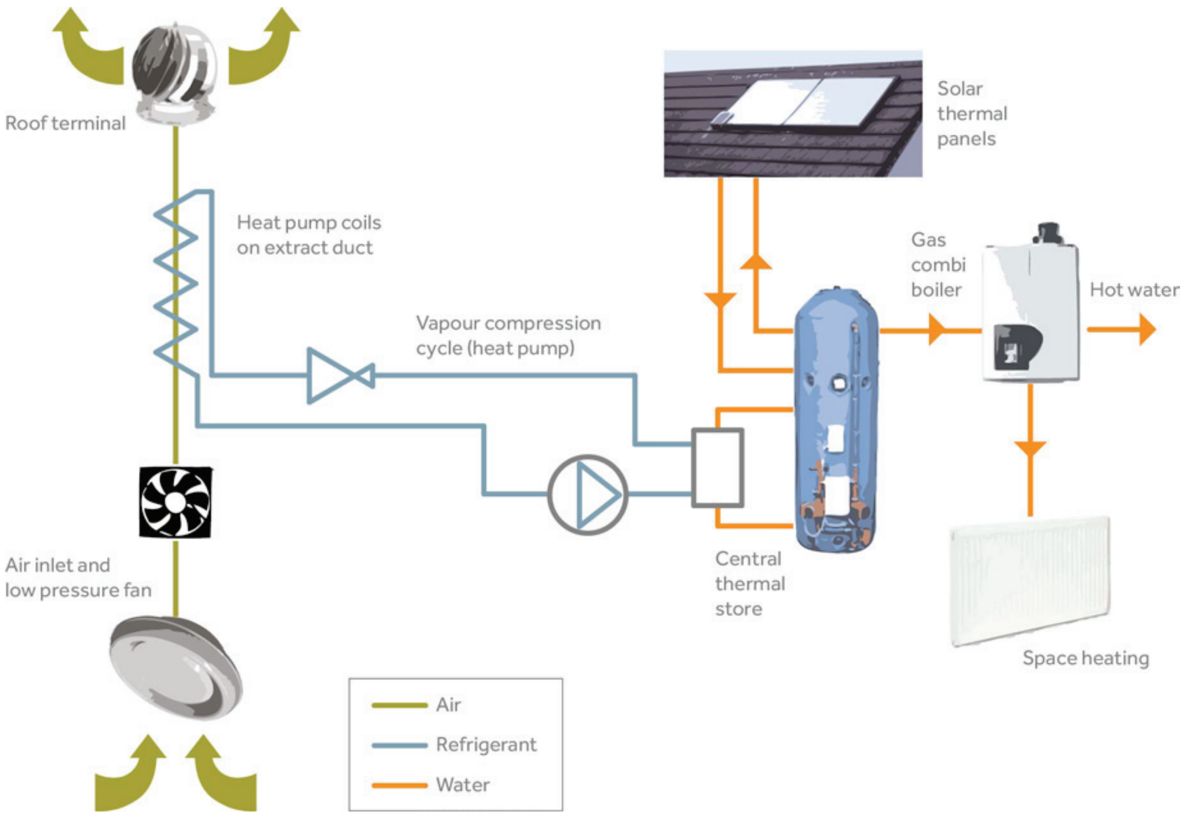


Figure 3.2: Case E, heating and ventilating system showing exhaust air heat recovery to hot water pre-heat

3.3.2 System choice and air quality

In principle, mechanical ventilation in airtight dwellings (below 5 ac/h @ 50 Pa) allows good control of air distribution and good indoor air quality.[4] In practice, performance depends on good design, commissioning and maintenance. The limited physical evidence shows that such performance was achieved in Cases D and H.

3.3.3 Using ventilation to deliver space heating

MVHR systems can be used to heat low energy dwellings, but this is possible only where heat demand is low. This is primarily due to the significantly different design requirements for a ventilation system as compared to a space heating system. The strategy is most developed in the Passivhaus model.

This strategy was applied only in the Case B terrace, in conjunction with a communal heating system. However, here the removal of radiators and the installation of MVHR in each dwelling were found disruptive by the occupants and, though subsequently corrected, the initial failure to commission the whole communal heating, ventilation and heat distribution system became a source of deep discontent among the occupants.

Although in principle elegant and economic, it appears that the decision to combine three relatively novel and complex systems with different supply chains laid the work programme open to significant risks.

Three of the projects that used whole house MVHR relied on existing radiators to provide space heating (Cases D, G and H). Using existing heating systems in this way will enable a wide range of heat supply systems (including boilers, heat pumps and district heating) to operate more efficiently.

In these cases, keeping MVHR separate from heating by retaining an existing heating system appears to have been a safer strategy – at least for the moment. It appears that the close coupling of sub-systems may make overall systems more vulnerable to failure, particularly where PTs are unfamiliar with the combinations in question.

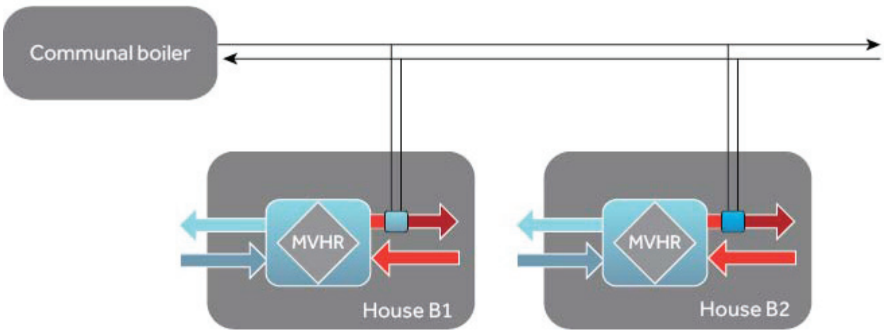


Figure 3.3: The main components of the space heating and ventilation systems in the Case B terrace. Hot water is supplied from the communal boiler by a separate hot water circuit. Both circuits run along the terrace through the attic spaces

[4] Note that this is not the same as the somewhat lower threshold for MVHR to significantly outperform MEV.

3.3.4 Practical considerations

Installation of ventilation systems is sensitive to house type and size. Most of the dwellings in the R4tF sample have less than 90 m^2 gross floor area. This is important because ventilation systems take up space for system units (containing fans, filters, heat exchangers and silencers) and ductwork, and to allow access for maintenance. Whole house MVHR has the highest requirements for space, followed by mechanical extract ventilation, passive stack systems and passive input ventilation systems. Single-room MVHR systems take up the least space of all (Case C), but in energy terms they are less effective than whole house systems. The space impact of ventilation systems was clearest in the Case B terrace. These houses had low ceiling heights and a low pitch roof, which meant that the MVHR system unit was installed on the landing adjacent to one of the bedrooms, leading to noise problems. High-level ductwork visually lowered the already low ceilings, making the dwelling seem oppressive. Concerns about space for MVHR were also raised by the occupants of Case D. These were resolved through negotiation with the PT.

Poorly designed and installed mechanical ventilation systems can be noisy – the occupant of Case A insisted on the removal of an MVHR unit from the kitchen for this reason. Minimisation of noise requires care in siting and installing system units, as well as the allocation of sufficient space for large, low velocity ductwork and possibly silencers (see Figure 3.4). Lack of space and siting system units immediately adjacent to bedrooms are likely causes of noise problems. Innovative design solutions, e.g. siting ventilation system units in porches, can significantly reduce space constraints and provide easy access for maintenance, but may be unacceptable in some neighbourhoods.[5]

Figure 3.4: MVHR unit showing input and exhaust ducting with silencers

[5] This solution was suggested during a final interview with the PT leader in Cases D and H.

All dwellings need openable windows, and occupants should feel able to open them when they need to. Keeping dwellings cool in summer takes up to ten times as much ventilation as is required to maintain air quality in winter. None of the ventilation systems installed in the R4tF sample has the capacity to deal with very hot weather, or to provide rapid purge ventilation in exceptional circumstances – when smoking, cooking, painting etc. Nearly all existing houses rely on natural ventilation for these purposes.

The use of solid wall insulation created thicker walls, making window-sills much wider. When these were located next to a kitchen counter-top, the occupants found it difficult to reach and operate window handles. This was especially distressing for occupants whose ventilation system was inoperable (Case B). This problem could be avoided if picked up early in the design process; if it is not addressed, it can significantly inconvenience occupants.

Case A shows the value of good innovative design that takes occupants' behaviours and lifestyle into account. This project made use of windows with secure side vents and a large automatic openable roof-light. Incorporating the latter into the design was a bold decision, and required significant structural alteration, but the result was a very high level of occupant satisfaction and pride.

3.4 Retrofit systems – technical and contextual constraints

Retrofit is subject to many constraints. PTs need to understand and negotiate these in order to develop solutions that strike an appropriate balance between top-level project goals (CO_2 emissions, energy use, cost) and risks emerging from real-world complexities. This section of the report considers constraints under the following four headings:

- technical
- contextual
- systemic
- social.

3.4.1 Technical constraints

Here, technical constraints means those constraints that can be analysed and understood from engineering and building physics perspectives. They include the following:

Internal wall insulation being fitted

- At its simplest, retrofit involves adding insulation to existing dwellings. Available insulants can be divided into two main groups – relatively cheap-but-thick (e.g. mineral fibre), and thin-but-expensive (e.g. aerogel). To achieve the U values typical in deep retrofits requires up to 400 mm of cheaper insulants in roofs and up to 250 mm in walls (e.g. Cases B, D and H).
- Minimisation of fan power in ventilation systems requires large, low air velocity ducts.[6] For such systems to provide an air change rate of 0.5 ac/h with low electricity consumption in typical dwellings requires duct diameters of 100–150 mm (see Figure 3.4).

[6] Fan power rises roughly as the cube of the duct cross-sectional area. Reducing duct diameter by 12% can double the electricity consumed by a ventilation system.

- With the exception of electric resistance heating, all heat supply systems operate more efficiently at low temperatures. Low temperature heating requires low heat loads, large air flow rates and large heat exchange areas – e.g. large radiators.

Though technical constraints are fundamental, some ease over time through technological development. A good understanding of constraints is likely to enable PTs to arrive at more effective "trade-offs" during the design process.

3.4.2 Contextual constraints

Contextual constraints include:

- heritage status (listed dwellings or dwellings in conservation areas)
- dwelling size, age, type and construction
- external environment, in particular factors such as driving rain, noise and pollution
- the clutter of sheds, outhouses and extensions that tend to gather around dwellings as they get older.

Heritage status was a determining factor in choice of envelope strategy in Cases C and E. Limited dwelling size was in part responsible for the low levels of occupant satisfaction in the three Case B houses, through its impact on the siting of MVHR system units and ductwork (Chiu et al. 2012). In Case H, external clutter – a neighbour's informal extension – caused a significant delay, while in Cases D and G, potential problems were used as opportunities to add value by including outbuildings within an extended heated envelope.

As the entire sample is located in London, the risk from driving rain is lower than average for the UK, but the risk of overheating is higher. Most of the properties suffer from high levels of external noise, air pollution and security issues. Key features of deep retrofits – high-performance windows and doors, and mechanical ventilation systems, particularly MVHR – will tend to reduce the impacts of all three.

3.4.3 Systemic constraints

Systemic constraints include:

- planning and building control
- utilities (electricity, gas and water)
- legalities, including leases
- contractual systems, codes of practice and cultures within the construction industry and its supply chains, from the national level down to the level of the individual company.

One of the features of rapid innovation is a significant increase in the need for effective communication within PTs and between PTs and their subcontractors, suppliers, clients and future occupants. Interfaces are a key feature of systemic constraints. Interface problems contributed to the delays in completion and commissioning that affected the Case B terrace.

Some PTs, e.g. the team responsible for Cases D and H, deliberately set out to create "islands of innovation" within which technology and practice could be fruitfully developed. These islands of innovation consist of small groups of individuals and companies that are relatively weakly connected to the culture, systems and practices of the rest of the UK industry, but that are very well connected with each other. Such islands of innovation are often interconnected, not just within the UK but internationally, through tenuous but extensive networks (e.g. the Sustainable Building Association, the Passivhaus community).

3.4.4 Social constraints

The primary social issue highlighted in this report and the main dilemma facing PTs is to decide whether to implement the retrofit with occupants in-situ, or to decant them to temporary accommodation. With budgetary constraints and economies of scale in mind, some housing associations and/or local authorities chose vacant properties (voids) for their projects (e.g. Case F) to give construction and installation teams a clear run. However, one PT turned the dilemma into a learning opportunity by choosing to implement its R4tF project in a void in order to provide a comparison with other projects they were undertaking where the occupants were in-situ (Case G).

Times to completion across the R4tF sample ranged from two months in Cases C and E (unplanned decants) to 15 months in Cases F and G (voids).[7]

Initial decisions to retrofit with occupants in-situ were reversed in Cases C and E when construction teams ran into difficulties insulating ground floors. The scheduled two weeks time to completion in both of these cases was extended to two months. Although Cases F and G were voids, the delays they incurred were similar in length to and for similar reasons to those in the in-situ Cases A, D, H and B1–B3. Delays were caused by a series of contextual, systems and systemic issues – vandalism in the neighbourhood and issues with contracting, planning, the supply chain and regulation (e.g. after insulation raised the height of the ground floor, the Case G team was required by Building Control to adjust the heights of all the treads in the staircase).

Although both Case C and Case E overran by more than six weeks, they were comparatively quicker to complete than the other cases in the sample. This seems to be due to a chain of cause and effect. Because both were Victorian terraced houses subject to heritage constraints, the PTs adopted simpler retrofit strategies that provided lower fabric and system performance. These simpler strategies avoided some of the systemic issues that were involved in the long delays suffered by other cases.

It is important to recognise that each case examined in this study is unique. It is difficult to draw robust conclusions about direct causal relationships between efficiency (defined by length of time for completion) and factors such as the status of occupation of the dwelling (void, decanted or with occupants in-situ).

To conclude, it appears that undertaking retrofits with occupants in-situ or decanting them both involve costs and lay projects open to risks in different ways. All PTs need to map these risks and chart an appropriate path through the decision tree of a retrofit project.

[7] The information about the length of completion in these cases was drawn from the occupants' perspective. This might not tally exactly with contract dates given by PTs in the "wash-up" meetings.

4. Observations on retrofit practices

4.1 Project Teams

To understand deep retrofit as a complex system, it is important to understand not only the technologies but also the practices involved.

Analysis of the post-occupancy interviews, the "wash-up" meetings, and the physical and individual interview data reveals not only the different sizes of organisations (large, medium/small) involved in these projects, but also significant differences in their operations. Several of the PTs appeared to operate broadly in a conventional way. Five out of the eight projects (Cases B, C, E, F and G) were led by local authorities or housing associations with the architects, energy consultants and contractors operating relatively independently. The other three projects (Cases A, D and H) were architect or energy consultant-led. These projects appeared to be more team-based and to display a greater degree of coordination, working together from the outset to establish design and performance goals and retrofit strategies. They tended to take greater account of clients' and occupants' needs, in particular engaging with occupants throughout the retrofit processes to resolve design, installation, commissioning and operational problems. What distinguishes Case A from Cases D and H is the fact that the PT for Case A stated explicitly that they were taking an integrated and occupant-centred approach.

4.2 Conventional practice in retrofit

Although no direct evidence regarding team processes and practices was gathered from Cases B, C, E, F and G, it was not difficult to infer from occupants' feedback and "wash-up" meetings that these teams operated on a relatively conventional basis: first, little attention was given to the specific characteristics, lifestyle and behaviours of the occupants, whether the properties were inhabited (e.g. Cases B1–B3) or void (Cases F and G); and second, there were often communication problems between occupants and PTs. Although some occupants were informed that they had been selected for the R4tF programme, they reported that they had had little opportunity to become involved in the design process. In one case, the occupant was unaware of the amount of retrofit work that was about to be undertaken (Case C). Several occupants stated that they found it difficult to communicate with PTs, and it appears that this had often resulted in occupants' feedback – about comfort and/or their ability to operate or control heating and ventilating systems (Cases B1–B3, E, F and G) – turning into complaints.

In the Case G "wash-up" meeting, it was observed that the PT lead (a local authority) had chosen a vacant property for the project because they were adamant that the retrofit design should not be tailored to suit any particular resident. So much so, that the family of five who eventually moved into the property had no understanding of either the purpose of the retrofit or the operation of any systems and monitoring equipment. They were also unaware that there was an MVHR system in the attic (Chiu et al. 2012). Interviews with occupants suggest that this approach – abstracting or subtracting the occupants from the retrofit process – had implications for occupants' acceptance of (Cases E and G) and adaptation to (Cases B1–B3 and C) new energy-saving systems, and significantly reduced the opportunity to promote energy-saving behaviours and lifestyles.

The conventional approach used in the construction industry emphasises predictability, reinforces uniformity and restricts the degree to which the social and behavioural needs of particular occupants can be addressed. Some of the PTs were partnered with organisations involved in multi-million-pound dwelling maintenance and refurbishment operations, and they appeared to have transferred this approach to the R4tF programme in the hope of producing a set of retrofit solutions that could be rolled out economically across the whole of the social housing stock (e.g. Cases B, F and G).

4.3 Integrated practice in retrofit

Although all the PTs approached the task of retrofit on a team basis, it was clear that some were more integrated than others, particularly in terms of the relationship between the design and build stages of the process.

The more integrated teams tended to work together from the outset to realise the goals of the R4tF programme. Led by the architect (Cases D and H), and supported by the local authority or housing association, team members often blurred their professional boundaries and adopted a range of different roles. This practice was explicitly adopted by the energy consultant for Case A (an architect and academic) who effectively led the project.

This individual had a long-standing working relationship with the project architect. The application of an integrated and occupant-centred approach towards the project was explicit. Perhaps as a result of his professional credentials and expertise and the commitment of all the team members, the design-and-build process was highly integrated. The outcomes of this project represent a balanced approach towards the physical challenges posed by the property, the behavioural and lifestyle needs of the occupants and the skilful negotiation of the constraints imposed by the current structure and practices of the building industry.

In Cases D and H (both employed a Passivhaus approach), the leadership role was formally taken by the architect. He had long-standing working relationships with a small mechanical and electrical consultant and a small number of contractors. By working collaboratively on a number of projects over the previous five years they had built up collective knowledge, shared practices and capacity for retrofit. The 80% carbon reduction target required by R4tF was consistent with the energy savings predicted by a Passivhaus approach.

Of these three properties, Cases D and H clearly succeeded in reducing energy use and fuel bills (the occupant's comments about the fuel bills suggest that this also applies to Case A). Case A, and to a lesser degree Case D, also added asset value by providing extra space through innovative design.

4.4 The role of communication in integrated practice

The more successful PTs not only engaged with the occupants to define their needs and understand their lifestyles, but also maintained close communication with them throughout the retrofit process (e.g. Cases A and D).

These teams exhibited two key levels of communication in relation to the design-and-build process: first, between the occupants and the PT; and second, within the PT itself.

Frequent formal meetings between the design team, client, occupants and energy consultants were structured into the work programme to allow all members to play their part in establishing performance goals. Strategies and options for achieving these goals were formulated, based upon an integrated analysis of how different retrofit systems would work (e.g. natural vs mechanical ventilation) given the lifestyle, behaviours and health conditions of occupants: smokers in Case A, hay fever and eczema in Case D, and chronic pulmonary obstructive disease in Case H.

While a liaison officer was often assigned by the local authority or housing association to engage, communicate with and inform the occupants about the retrofit process, in Cases A, D and H an informal engagement and communication process between the occupants and the PT went on throughout. This provided close to real-time feedback on design issues, installation delays and difficulties, and performance (MVHR in Case A, a cold bedroom in Case D). The PTs' responses to occupants' issues allowed iterative learning by all concerned.

Finally, the availability of a full range of physical monitoring data for Cases D and H appears directly related to the level of personal engagement by the architect with the occupants. No other PTs in the study exhibited such a relationship with the occupants.

5. Interactive adaptability

Interviews and walk-throughs with occupants have enabled the research team to catch a glimpse of the process of mutual adaptation between dwelling, systems and occupants that took place during and after the retrofits.

5.1 System adaptability

The evidence from the R4tF sample shows how the goal of deep retrofit led to complex systems that were in some cases difficult for occupants to understand and operate.

While the goals of retrofit were set by the R4tF programme, not all PTs started with the same knowledge, capacity and experience in retrofit, and they approached their projects in different ways. In other words, each case was different.

It was observed that those PTs that took a more integrated approach to their project were likely to design systems that were more responsive to occupants' needs and more adaptable to occupants' lifestyles and behaviours. Table 5.1 provides examples of such adaptations.

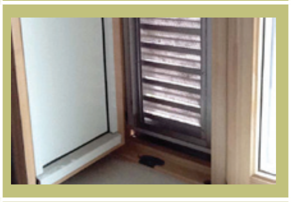
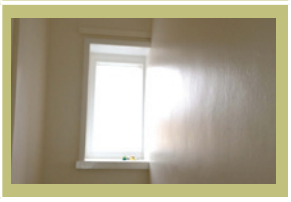
Case	Occupants	Design solutions	Photos
A	Smokers, concerns with security	Windows triple-glazed with large secure side vent	
	Dark interior Heavy use of tumble dryer, need for more storage space	Automated roof-light with integral drying facilities, additional half storey providing storage in original roof void	
	Concerns over noise generated by ducted MVHR unit installed in kitchen	MVHR unit removed and replaced with individual unit installed in bathroom	
D	Family of eight, intensive and frequent cooking One family member suffered from hay fever and eczema	Passivhaus retrofit strategy, incorporating whole house MVHR	
	Needed more room, and more daylight at back of house Dilapidated external WC	Larger window for rear of ground floor Incorporated external WC into the thermal envelope thus providing more space	
	Concerns with impact of MVHR ductwork on cupboard	Duct route altered	
	Concerns about loss of space to internal insulation	Insulation thickness reduced	

Table 5.1: Examples of retrofit solutions adapted to occupants' needs
(Source: LaiFong Chiu, UCL-Energy)

The ability of these teams to engage and communicate both internally and with the occupants throughout the process was crucial in helping PTs and occupants to understand and adapt to each other's needs. While the goal of carbon and fuel bill reductions was never far from PTs' minds, they were more flexible in responding to emergent system and contextual constraints (see Table 5.1).

In contrast, some PTs attempted to minimise the need for occupants to interact with key systems (in Cases G and F, the MVHR system) by keeping them out of reach and out of sight. The challenge ultimately is to develop solutions for large-scale roll-out and while it can be challenging it is very important to include the occupier in the process.

The issues surrounding conventional as opposed to integrated practice and the impacts of contractual and process fragmentation within the construction industry are well known. However, it is important to note that the local authority leading Case G consciously attempted to move towards more integrated practice by building retrofit capacity and competence within its own organisation.

5.2 Occupant adaptability

The effective functioning of a complex energy-saving system requires the user to understand and be able to use the system effectively. However, most PTs did not ensure that occupants acquired the necessary knowledge and skills to do this.

Only one occupant (Case D) had a significant understanding of the systems installed in their home. The majority of the occupants in the study (e.g. Cases B1–B3, C, E, F and G) were found not to be able to programme their heating systems. They also did not understand the functioning of their ventilation systems and some had disconnected them out of sheer frustration or bafflement (e.g. Cases E, F and G).

5.2.1 Barriers to adaptability

The following barriers to adaptation for occupants were observed:

Poorly considered handover process: While the handover process would have been a good opportunity to help occupants understand and operate systems, most handovers were done without consideration of how people with diverse social backgrounds and cognitive abilities learn.

Insufficient time allocated to the handover: It is evident from occupant interviews that a handover/training process of less than half a day was insufficient to help them to understand the systems in their homes.

Hard-to-understand control interfaces: The control interfaces on some systems were hard to understand and/or to operate (Chiu et al. 2012).

Inappropriate or missing information: In some cases, occupants were given manuals intended for professional installers – these are difficult for members of the lay public to digest (Case E).

5.2.2 Facilitating adaptability

The following practices were observed to facilitate occupant adaptability:

Supporting and engaging with occupants throughout the retrofit process: The occupant in Case D had gained a clear understanding of the systems and how to operate and maintain them (e.g. changing the filters in the MVHR system) although he was not expected to do so.

Fostering a feeling among the occupants of control over the build process: Occupants in both Cases A and D were able to negotiate what measures and systems would be installed, and how, during the retrofit process. The opposite was true for the occupants of the Case B terrace, in particular, where a sense of powerlessness set in (Chiu et al. 2012).

Engendering a feeling of control over systems: Where the systems and control interfaces gave clear and immediate feedback on operation, the occupants gained a feeling of control (e.g. Case A's automated roof-light and Case D's MVHR interface).

Building trusting relationships: Trusting relationships between PTs and occupants helped to address a range of emergent issues, including cold-bridges, roof leaks and cooking smells (Case D), rapidly and successfully.

5.3 Dialogue and communication as key to interactive adaptability

It is hard to overstate the benefits of effective dialogue and communication at each stage of the retrofit process. The following practices were observed to be of value:

Supporting PTs in the design process: With open dialogue and communication, occupants provided design teams with invaluable information about their lifestyles, habits and energy consumption behaviours.

Helping occupants to cope with disruption: Keeping occupants informed of progress, coupled with a well-managed work programme, not only helped occupants to cope (Cases A, D and H) but also affected their overall satisfaction with the retrofit process.

Improving understanding of systems: Where occupants observed the installation of systems, they appeared more receptive to explanations and instructions on how to operate them (Case D).

Improving learning on both sides: Trusting and collaborative relationships founded on good communications helped PTs to obtain high quality monitoring data, with occupants understanding and respecting the value of monitoring, and PTs having ease of access to the property (at time of writing, Cases D and H were the only cases to have produced comprehensive physical data). These data helped PTs to improve their understanding of the performance of systems and the extent to which occupants had learned to control them.

Dialogue and communication between PTs and occupants require a participatory relationship between all concerned. Driven by the ambition of large-scale retrofit and the efficiencies, in principle, offered by conventional practice, some social landlords viewed participatory relationships with individual occupants as leading to tailored designs that could not be easily replicated across their housing stock. This way of thinking overlooks the key role occupants play in supporting learning at this stage in the development of the retrofit industry, and the differences between new-build and retrofit.

The counter-argument is that occupant participation could be costly in large-scale retrofit in social housing. However, the R4tF programme involved technologies and processes that are to a significant degree experimental in nature, and most PTs lacked a depth of experience in their design and application to different house types. Under these circumstances, inductive learning is crucial.

6. Outcomes

Data on outcomes were collected in the following categories:

- physical data: energy use, CO_2 emissions, internal temperatures and indoor air quality provided by PTs
- occupant satisfaction with the process and with the final result
- any change in health conditions after retrofit
- wider impacts on occupant behaviour
- costs of retrofit (see Section 7).

Some physical data were not yet available making it difficult to make definitive statements about physical outcomes. At time of writing, internal temperature and internal CO_2 data were available for only four dwellings (Cases D, F, G and H). Solar photovoltaic data were available for two (Cases D and F). In addition, gas and electricity data were available for Cases D and H. Data from physical monitoring are supplemented by occupants' reports on internal temperatures in all cases except Case G, and on fuel bills in some cases. The following discussion of outcomes will therefore focus mainly on cases with physical data.

6.1 Internal temperatures

A range of internal temperatures was recorded in dwellings after retrofit. In four of the dwellings (Cases A, C, D and H), occupants chose to operate their houses at temperatures significantly above those commonly found in UK houses.

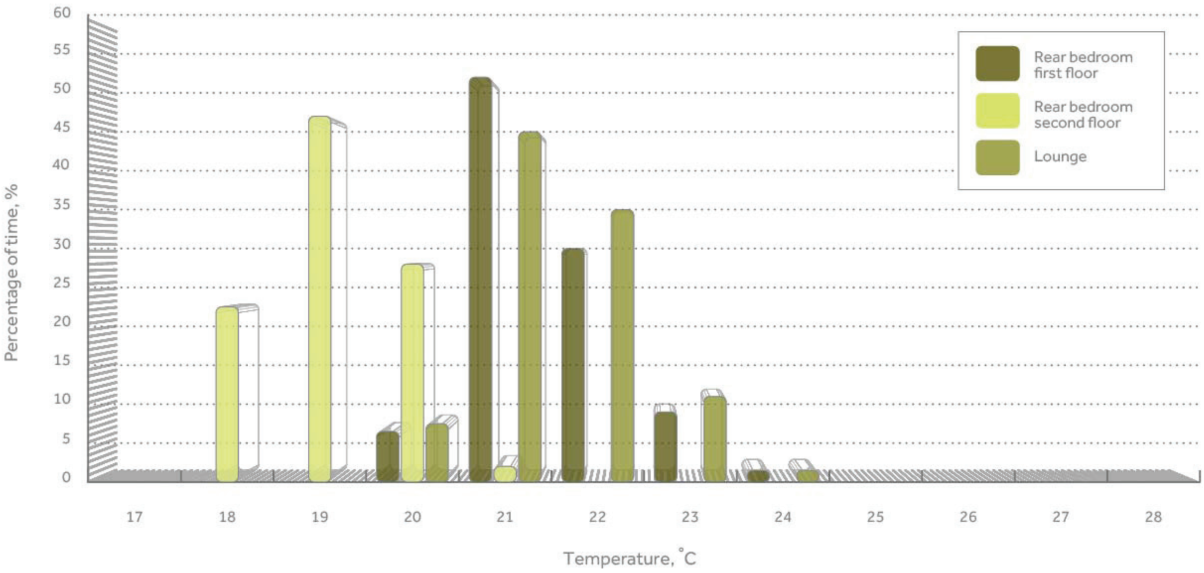


Figure 6.1: Case D, internal temperature data, July 2011 – August 2012 (441 days)
(Source: PTs)

Although internal temperatures were not measured in any of the houses before retrofit, the temperature after can be compared with the estimate of the average internal temperature in England of 17.3°C (Palmer and Cooper 2011). Internal temperatures in Case D never fell below this average, and were typically 3–5°C higher. It was noted that the rear bedroom in Case D was significantly colder than the rest of the house because of poorly insulated eaves. This defect was corrected in 2012.

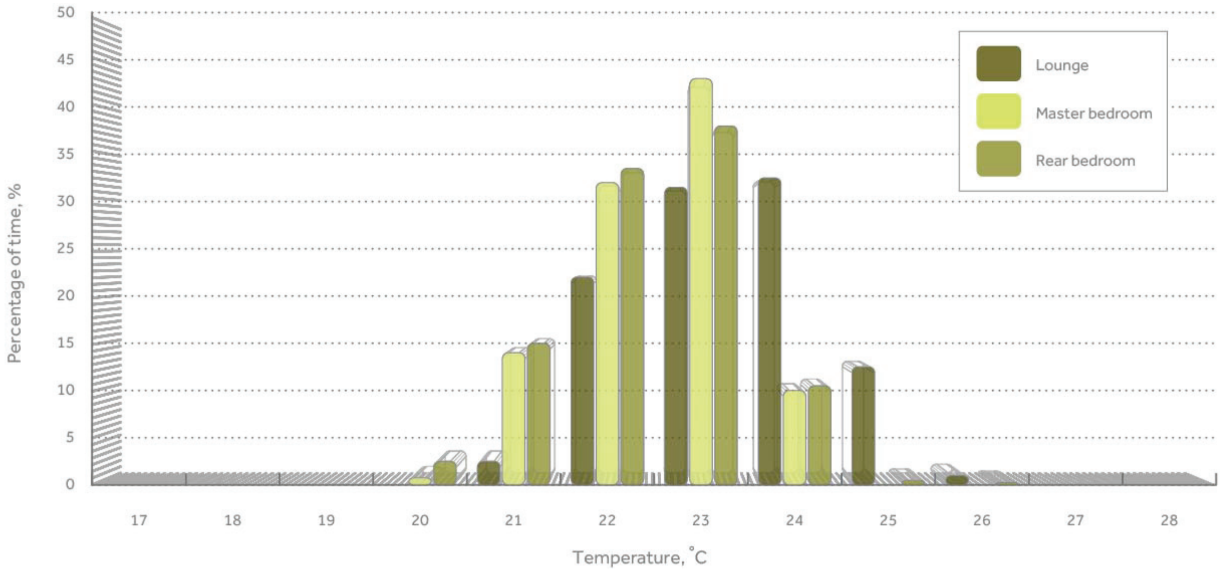


Figure 6.2: Case H, internal temperature data, September 2011 – July 2012 (294 days)
(Source: PTs)

Internal temperatures in poorly insulated dwellings tend to drop during winter. The following graphs show how internal temperatures vary with external temperature for Cases D, F, G and H. In three of these cases, internal temperature remained high when external temperatures dropped below 0ºC.

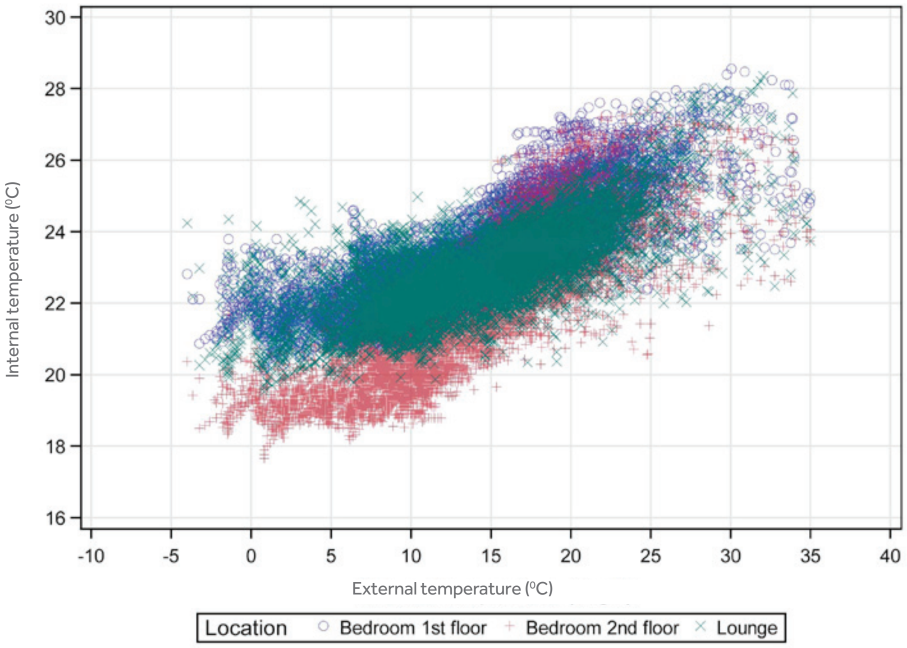


Figure 6.3: Case D, internal versus external temperature, June 2011 – August 2012 (441 days). Data in red are for a bedroom affected by excessive thermal bridging during this period
(Source: UCL-Energy based on R4tF data)

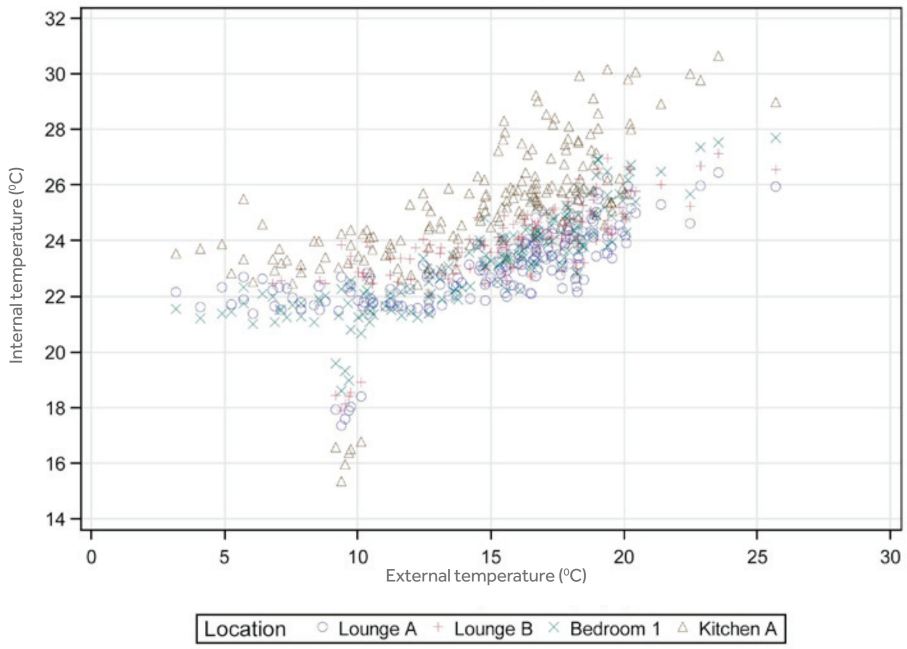


Figure 6.4: Case G, internal versus external temperature, March 2011 – December 2011 (8 days)
(Source: UCL-Energy based on R4tF data)

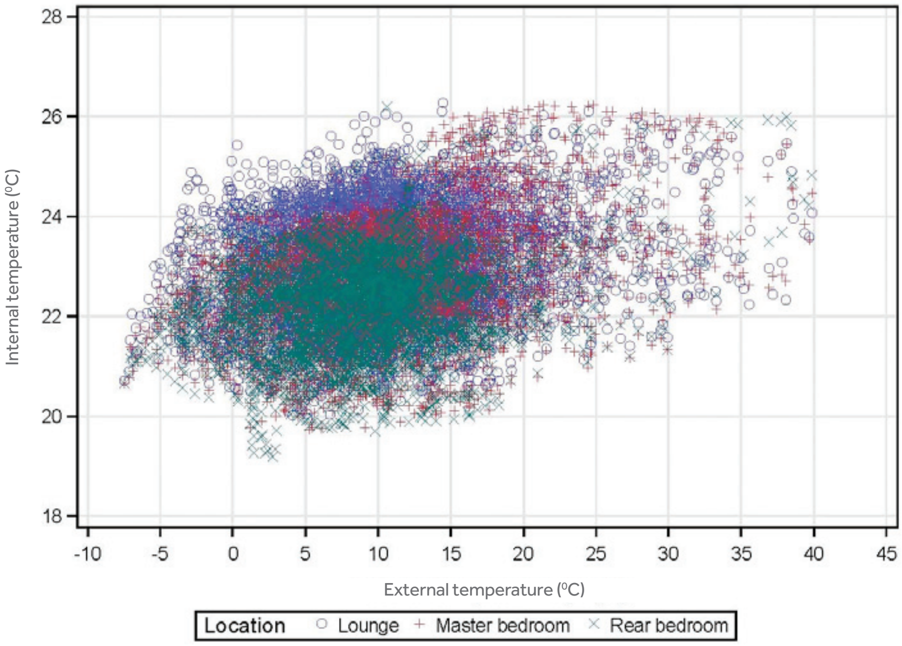


Figure 6.5: Case H, internal versus external temperature, September 2011 – July 2012 (294 days) (Source: UCL-Energy based on R4tF data)

Not all of the sample houses ran at such high internal temperatures. Occupants in Cases B3, C and E stated that they preferred lower internal temperatures – between 15 and 18°C for Case E. Figure 6.6 shows internal versus external temperature variation for Case F, whose occupants stated that one of the rooms in their house was cool.

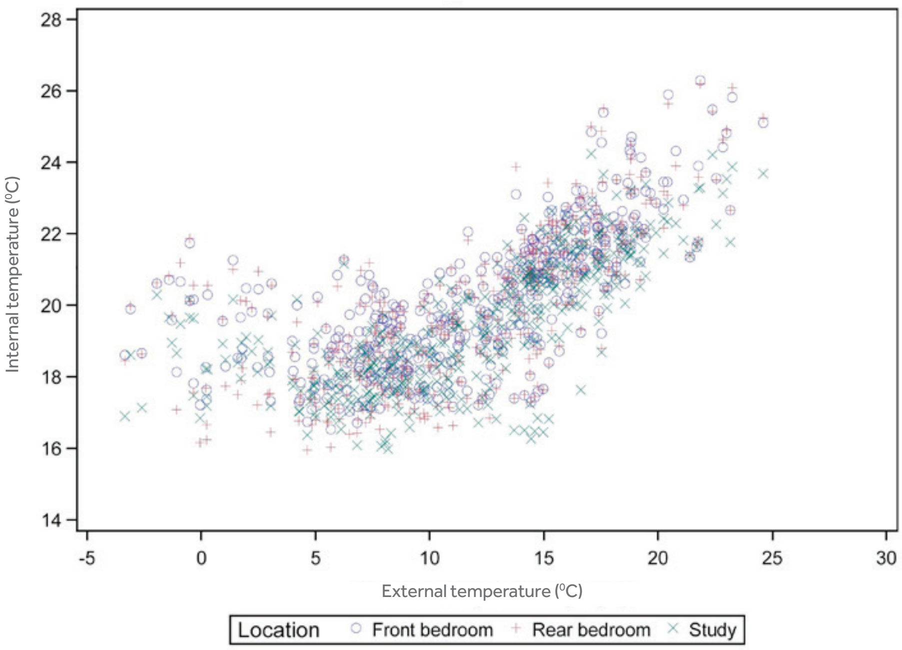


Figure 6.6: Case F, internal versus external temperature, September 2010 – August 2012 (18 days) (Source: UCL-Energy based on R4tF data)

6.2 Energy consumption and CO_2 emissions

Comparison of data from before and after retrofit for Cases D and H suggests significant savings in gas and electricity consumption.

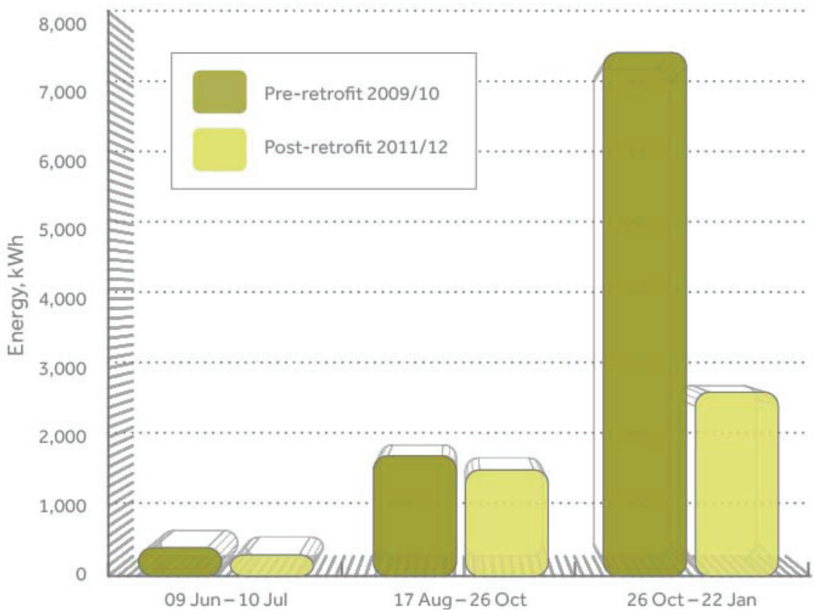


Figure 6.7: Case D, gas consumption data for heating, hot water and cooking, before and after retrofit (Source: PTs)

These changes in gas consumption are large. Gas consumption for Case D is estimated to have been around 18,000 kWh a year before the retrofit, somewhat above the UK median of 16,500 kWh. After the retrofit, gas consumption appears to be around 9,000 kWh a year, a 50% reduction.

For Cases D and H it was possible to construct estimates of annual gas and electricity use after the retrofit using around six months of gas meter data and rather less electricity data. These were converted to CO_2 emissions using carbon intensities of 0.194 $kgCO_2$/kWh for gas and 0.58 $kgCO_2$/kWh for electricity. In the absence of gas and electricity meter data from before the retrofit, these figures were compared with the median gas and electricity use and equivalent CO_2 emissions for all UK gas-heated dwellings. The figure of approximately 2.8 tCO_2/a for both Cases D and H represents a reduction of about 45% compared with the 5.1 tCO_2/a median for the national UK housing stock (OFGEM 2011).

Primarily because of the effort PTs put into the fabric of Cases D and H, the highest internal temperatures and lowest energy use would be expected in these houses. Not all of the retrofits operated at such high internal temperatures, and, as noted above, some occupants chose not to. But a recurrent theme, even in those houses (Cases B1–B3) where heating systems had not been fully commissioned, was that the retrofitted houses were easier to keep warm than before. It appears that, done well, deep retrofit transforms the internal conditions in dwellings at the same time as halving overall CO_2 emissions.

6.3 Occupant satisfaction

Post-occupancy interviews offer considerable insight into the level of occupant satisfaction with the retrofit process and the end result, and the reasons for both. Figure 6.8 shows the level of satisfaction reported by occupants. Interviews were conducted in late 2011 and early 2012. The following observations can be made:

- Qualitative evidence from the interviews shows high levels of disruption to occupants' lives, with six out of ten cases dissatisfied or very dissatisfied with the retrofit process. There were four exceptions: in Cases F and G the occupants were allocated the house after the retrofit; and in Cases A and H the occupants formed very good relationships with their PTs and this appears to have influenced their evaluation of the process.
- Of the six cases that were dissatisfied with the retrofit process, three were satisfied or very satisfied with the end result. In Cases A and D, the reversal was complete.
- Cases B1–B3 remained dissatisfied or very dissatisfied after the retrofit. The reasons for this were complex but dominated by the fact that at the time of the interview (early 2012) the heating and ventilating systems in the terrace had still not been commissioned. Despite this, the occupants in Case B2 were less dissatisfied with the end result than with the process. They recognised that, despite everything, their retrofitted home was more comfortable and easier to keep warm.

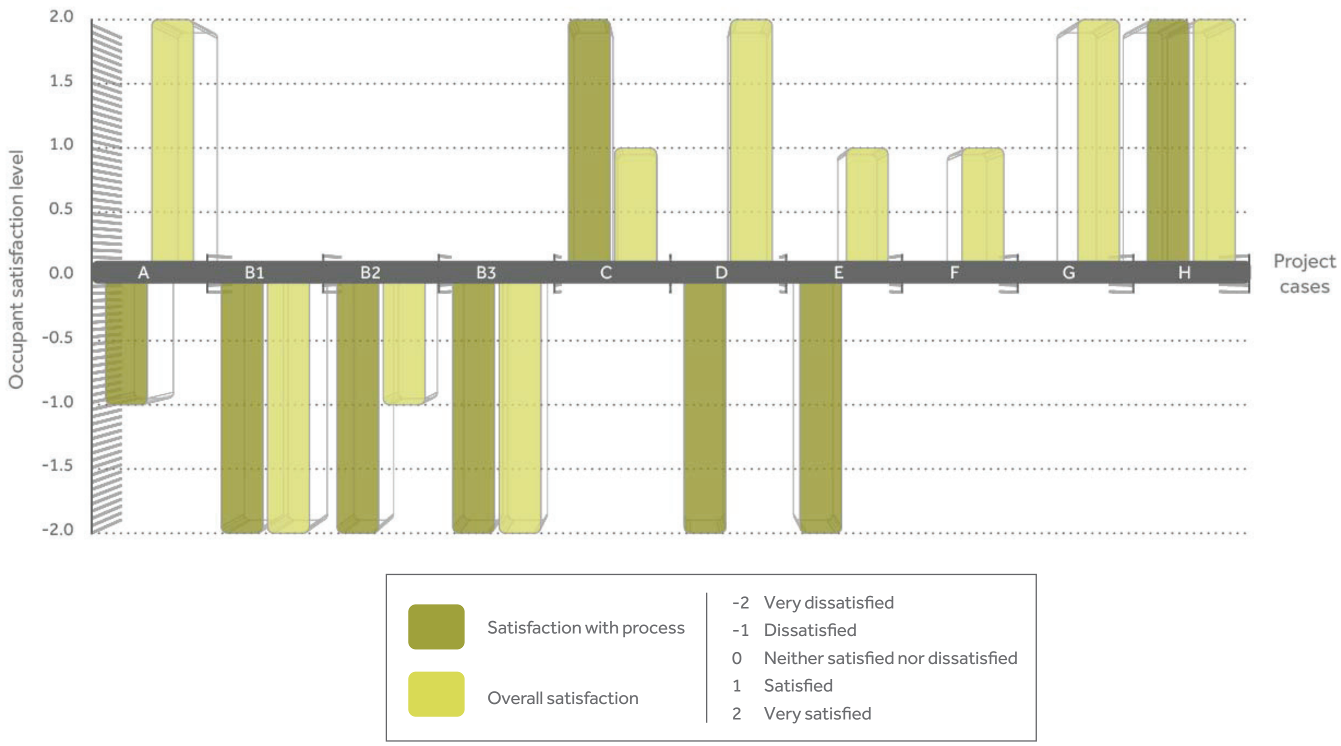


Figure 6.8: Occupant satisfaction with the retrofit process and outcomes

6.4 Health conditions

Housing and health is a difficult and complex subject, and this project can offer only initial indications as to outcomes. The clearest indication from the sample was a statement by the occupant in Case D that the eczema and asthma suffered by a member of the family had improved following the retrofit.

It was reported that certain health conditions (i.e. asthma and chest infections) were adversely affected during the retrofit due to the effects of poor thermal conditions prolonged by the delay in the construction process (e.g. Cases B1 and B2). Health impacts potentially arise from stress, difficulty with preparation of food (due to reduced or unfamiliar facilities and lack of access to crockery, cutlery, ingredients and food storage) and dust. The first two of these may apply whether occupants are decanted or the retrofit is undertaken around them.

7. Economics of retrofit

It is important to preface this section with a contextual caveat regarding direct scale-up of the findings to mass retrofit. The approach taken by the PTs, and consequent costs of these projects, was largely determined by the parameters and objectives of the Technology Strategy Board R4tF competition (TSB 2009). This was focused particularly on encouraging innovative, collaborative "whole house" design, aimed at achieving very high levels of carbon reduction – 80% of "controlled emissions". This was to be achieved within an overall budget of £150,000 per dwelling, including design, management and activities such as physical monitoring that were necessary to support the research objectives of R4tF. These performance targets lie far beyond current practice in the UK and it is unsurprising that PTs found them challenging. Given the small-scale, innovatory nature of each project, the underdeveloped supply chains and the need to support and document learning within the PTs, cost and cost-effectiveness were not the primary goals of R4tF. Full information is not available for all of the ten R4tF cases, but PTs appear to have spent in excess of £100,000 on each retrofit.

A critical question for the future is whether retrofit at scale can be made economic. Factors and strategies that may help to achieve this are identified and discussed below.

Like all activities, retrofit takes place in an economic context. A recent OFGEM report shows that the median UK dwelling spends just over £600 a year on gas and just over £400 a year on electricity. Assuming optimistically that retrofit reduces both by 75%, the most that the median energy bill can be reduced by is about £750 a year. In practice, the reduction is likely to be less than this. But taking the figure of £750 as a rough guide, the question is, how much money can be spent economically to reduce bills by this much?

For work funded under the forthcoming Green Deal, this is likely to be determined by the so-called Golden Rule. This states that energy-saving measures have to pay for themselves over their lifetime. With assumptions about physical lifetimes and interest rates, the Golden Rule can be translated into limits on retrofit costs (Figure 7.1). These can then be compared with the actual costs of R4tF sample.

For Case H, the total cost of the retrofit (excluding design and management costs) was around £115,000, between six and nine times what could be justified under the Green Deal. This can be restated in terms of the carbon price that would be needed to enable these schemes to break even. Break-even carbon prices over a 50-year period are around £750 and £850 per tonne of CO_2 for Case D and Case H respectively. These figures are ten times higher than the recently proposed carbon floor price for 2030, and three to four times higher than estimates of the carbon price for 2050. The question is whether or not a combination of retrofit cost reductions and the capturing of additional streams of value can close the gap.

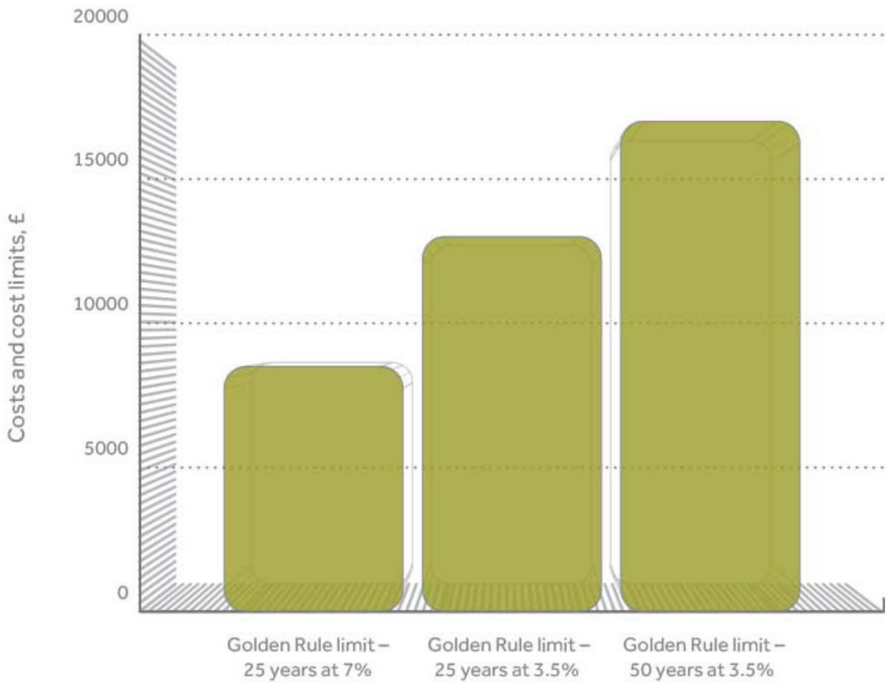


Figure 7.1: Costs and cost limits under the Golden Rule

7.1 Capturing added value from retrofits

In principle at least, all of the PTs added value to existing dwellings, e.g. through replacement of kitchens and improvement of gardens. However, several PTs went further than this, deliberately approaching the problem of difficult economics by trying to maximise the non-energy value of the dwelling. The clearest example is Case A, where an additional half storey, with a roof-light to bring daylight into the heart of a deep-plan terraced house, was added. As noted earlier, the occupant placed significant value on these changes. More modest changes include extending the thermal envelope to bring unheated external WCs and other peripheral spaces into the heated part of the dwelling (Cases D and F – such features are common in hard-to-heat homes). Adding value to existing properties in this way is likely to be most important in the owner-occupied and co-ownership markets. It is also worth remembering the poor conditions that prevail in some of the existing housing stock, exemplified in the sample by streaming single-glazed windows in Cases C, D and E. Retrofit significantly improves people's lives in ways that cannot be reduced simply to lower energy bills.

Health benefits are likely to provide an additional source of added value. Although the effects are only self-reported, the occupants in Case D reported improvements to their family's health. The high internal temperatures in several of the retrofits (the physical data are most complete for Cases D and H) are a further category of added value. The occupants in Cases A, C, D and H have the choice of running their houses at mean internal temperatures typical in the UK housing stock – around 19°C – but instead ran them at between 21 and 25°C.

7.2 Reducing the cost of retrofits

Several PTs commented on the economic problem in their online project blogs (www.energysavingtrust.org.uk/Organisations/Business-services/Free-resources-for-housing-professionals/Retrofits/Retrofit-diaries/) and in interviews with the UCL-Energy team. In principle, costs can be reduced by economies of scale, by systematisation of retrofit practice, by shortening and developing supply chains and by careful reduction of the scope and ambition of retrofits. The clearest example of the first is Case B, which involved the retrofit of a terrace of four dwellings on a gross budget of £300,000 (i.e. two single awards of £150,000). The PT for Case B explicitly set out to prototype a retrofit solution which included a shared heating system that could, in principle, be rolled out across the rest of the estate.

The PTs responsible for Cases D and H provide an example of systematisation of practice at several levels. The architect (an SME) who led both teams has spent the last six years refining designs and working practices and developing a network of suppliers and contractors to support Passivhaus retrofit. The fact that his practice undertakes its own physical monitoring underpins a knowledge-based business model which has allowed it to develop impressive technical and process expertise in a relatively short time.

The relatively small scale and short history of the UK retrofit market means that many components and systems need to be sourced from overseas. Consequences include the commissioning difficulties that were encountered by the Case B PT (with control panels that initially displayed in German), and glazing that needed to be imported from Japan (to the astonishment of the Case E occupant). Immaturity of the UK supply chain may also have been responsible for the problems with the windows encountered in Case B (Chiu et al. 2012). It appears that supply chain immaturity was one of the causes of delays to completion in all ten cases – with consequent but currently undefined impacts on costs.

The option of reducing costs by reducing the ambition of retrofits is one that is acknowledged, in passing, by several teams. The Technology Strategy Board's target for R4tF – an 80% reduction in CO_2 emissions – was deliberately challenging. Low carbon retrofit is characterised by high costs for key sub-systems, for example external solid wall insulation. The marginal payback time of the last millimetre of insulation rises as the square of the total thickness – increasing the thickness of insulation in a wall from 50 mm to 250 mm means, crudely, that the last millimetre takes around 25 times as long to pay back. Nevertheless, the high fixed costs associated with measures such as external solid wall insulation mean that the payback time for the whole insulation package is flat over a wide range of insulation, with steeply rising costs as carbon reduction targets increase.

Some of these costs can be partially offset by savings – e.g. on the cost of heating systems. Opportunities to reduce cost include:

- moving to simpler systems – e.g. mechanical extract ventilation instead of whole house MVHR (Case E), or to simpler versions of MVHR such as cascade ventilation (Rainer 2011) or single room systems
- accepting lower specifications for insulation – a wall U value of around 0.2 W/m^{2}K in Case F required the addition of internal aerogel insulation to a wall that was already insulated with polyurethane foam insulation to 0.35 W/m^{2}K; the additional layer of insulation had a very long payback time

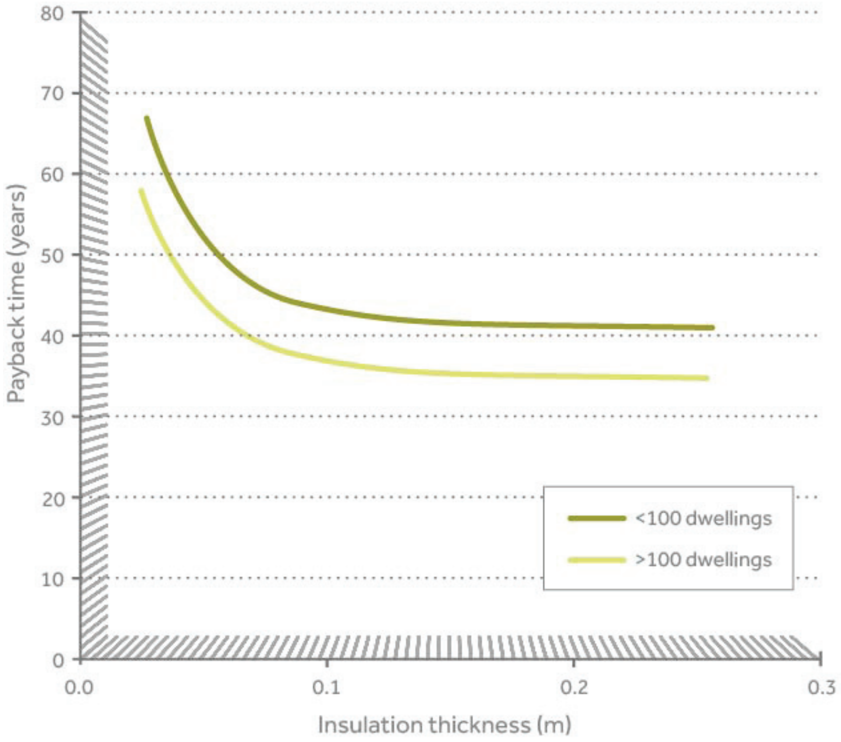


Figure 7.2: Payback time for external solid wall insulation[8]

- accepting that the individual dwelling is not an island which needs to achieve the whole of the UK's 2050 CO_2 reduction target on its own – the clear implication of current energy and CO_2 policies is that energy supply systems will decarbonise, and that the objective must be to achieve the most cost-effective solution taking both end-use and supply systems into account.

This last point was acknowledged by the PT of one project that did not make it through the first round of the R4tF competition. This project was based on a strategy of linking a retrofit to an existing combined heat and power/district heating system in south London. In principle at least, this allowed lower levels of thermal insulation and a highly cost-effective solution.

Finally, it appears likely that energy prices will rise in the future, whether because of carbon pricing to drive energy efficiency and decarbonisation across the economy, or because of increased global competition for fossil fuels. This has recently been recognised through the UK Government proposals for a carbon floor price. If pursued, these would see gas prices double by 2030, halving payback times for low carbon retrofit. Put another way, current gas prices appear to be significantly below the long-term cost of low carbon heat in the UK, and are therefore an inappropriate basis for costing retrofit.

[8] Published cost estimates for EWI cover a wide range. Based on cost estimates and analysis by Purple Market Research (2009), mid-2012 gas prices, an uninsulated wall U value of 1.4 W/m^2K and a mean internal temperature of 20°C. The shape of the graph is insensitive to the detail of these assumptions.

8. Conclusion

Social housing represents a substantial market for SMEs to exploit retrofit as a business opportunity. This is driven by a government target for the UK housing sector to achieve a reduction of carbon emissions of 29% from the 2008 level by 2020 (DECC 2009).

The present study of a selected sample of R4tF sample highlights the challenges faced by the construction industry when undertaking low carbon retrofits efficiently and cost-effectively to realise this ambition.

It has been difficult to determine physical outcomes for all the retrofits as the full monitoring data are not available yet.[9] But together with other sources of data, these cases tell a complex and convincing story of both success and room for improvement.

The insights gained from this investigation can be summarised as follows:

1. Retrofit involves a complex intervention in a complex system, which includes both the dwelling and its occupants.

2. Retrofit strategies, the nature of the risks to programmes and the likelihood of satisfactory outcomes depend on house types and context. Certain types, typically more modern dwellings, based on geometrically simpler house types and without clear heritage value, support relatively simple retrofit strategies. Others, particularly older dwellings with significant heritage value, do not.

3. Successful retrofits appear to support higher internal temperatures and levels of comfort, and generate high and in some cases very high levels of occupant satisfaction.

4. The costs of deep retrofit are, at present, significantly more than the likely limits on expenditure under the Green Deal. More work is needed to establish how far the funding gap can be closed by a combination of accounting measures to reduce interest rates, reductions in retrofit costs, carefully thought-through reductions in retrofit ambition, and identification and measurement of additional streams of value such as benefits to health.

5. There is abundant evidence that the supply chains needed to support large-scale retrofit are underdeveloped. This suggests that to develop a UK retrofit industry, government should consider at least one if not several further pilot programmes, intermediate in scale between R4tF and full-scale retrofit. More work is needed to develop local/UK supply chains and to embed the knowledge needed to successfully routinise large-scale retrofit.

6. One option to build capacity at reduced cost and risk is to focus on less difficult dwelling types. But no dwelling type should be counted as simple, and problems resulting in programme delays and major adverse impacts on occupants can arise in any dwelling.

[9] The Technology Strategy Board plans to release the data for public access during spring 2013.

7

Some retrofits incorporate interventions of exceptional design value that almost certainly add significant asset value. The combination of such design interventions with deep retrofit may provide a business opportunity, particularly in private and shared equity housing, and would be supported by changes to Building Regulations such as Consequential Improvements. Different strategies are likely to be needed in social and privately rented housing.

8

There is evidence that project outcomes were influenced by the practices of individual PTs. PTs that were relatively highly integrated also engaged and communicated with the occupants better. This seemed to promote better design and better management of occupants' experience of disruption, and produced better information to help occupants to adapt to their new environment and to support learning by PTs.

9

PTs which took a more conventional approach towards retrofit were driven by the desire to implement large-scale roll-out based on the learning opportunities offered by the R4tF programme. However, such ambition may be premature.

10

The Passivhaus approach could be seen as one way of making deep retrofit routine, as the knowledge base of the Passivhaus community accumulates on a case-by-case basis. Passivhaus standard retrofit requires not only technical know-how but also skills in building supply chains and systems of support within PTs. As knowledge, the skills base and networks grow, a position may be reached in which PTs will be able to respond routinely to a wide diversity of house types and households. However, this is some time off and, until then, the notion of project coordinator/manager may be the key to measurable success (for further information see the Institute's Building Opportunities for Business Low Carbon Domestic Retrofit Guide 5).

11

Occupant satisfaction will be crucial to the longer-term success and continuation of any large-scale retrofit programme. Evidence from this study suggests that problematic retrofits have major adverse impacts on people's lives, and on the reputation of the industry when news spreads. This should be taken as a risk that needs to be managed in the retrofit industry.

12

Innovation necessarily involves risk. While learning from success is often easier than learning from apparent failure, the lessons from the latter may have greater value and long-term impact.

13

Significant business opportunities appear to flow from the integration of skills and functions within existing SMEs, and the creation of networks of companies capable of sharing learning and reducing risks.

9. Glossary

Cold-bridge/Thermal bridge – a junction where insulation is not continuous, resulting in increased localised heat loss.

Fabric first – describes the retrofit strategy which advocates insulation of the building fabric as the priority measure.

Interstitial condensation – describes water condensing out of moisture-laden air inside a porous building material, such as brick.

Passive stack ventilation system – vertical ventilation pipe terminating above the roof, which uses the natural buoyancy of warm air to draw air out of a dwelling. Such systems can be mechanically assisted through the addition of a low power fan.

Passivhaus strategy – describes the implementation of Passivhaus principles when retrofitting an existing building.

U value – the measure of the overall heat transfer coefficient in a building element such as a wall, floor, window or roof. It is measured in watts per metre square kelvin (W/m^2K). A low U value usually indicates high levels of insulation.

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