Low carbon housing

Lessons from Elm Tree Mews

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This report sets out the findings from a low carbon housing trial at Elm Tree Mews, York, and discusses the technical and policy issues that arise from it.

The Government has set an ambitious target for all new housing to be zero carbon by 2016. With the application of good insulation, improved efficiencies and renewable energy, such a target is theoretically possible. However, there is growing concern that, in practice, even existing carbon standards are not being achieved and that this performance gap has the potential to undermine zero carbon housing policy. The report seeks to address these concerns through the detailed evaluation of a low carbon development at Elm Tree Mews.

The report:

- evaluates the energy/carbon performance of the dwellings prior to occupation and in use;
- analyses the procurement, design and construction processes that give rise to the performance achieved;
- explores the resident experience;
- draws out lessons for the development of zero carbon housing and the implications for government policy; and
- proposes a programme for change, designed to close the performance gap.

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Executive summary

This report details the findings from the Elm Tree Mews low carbon housing field trial and discusses the broad lessons and policy implications for the development of new build, low and zero carbon housing. The research was conducted by the Centre for the Built Environment (CeBE) at Leeds Metropolitan University. The research project was supported by the Joseph Rowntree Foundation (JRF) and undertaken in conjunction with the scheme developers, the Joseph Rowntree Housing Trust (JRHT). The broad aim of the research was to evaluate the extent to which the performance of low energy housing, such as that of the Elm Tree Mews housing scheme in York, meets the specifications and predictions of the design brief. Furthermore, it helped to understand the various factors, processes and behaviours that can influence both the as-built energy performance and the consumption of energy in use. The work does not purport to evaluate any other aspects of performance such as general aesthetic quality. The conclusions and implications detailed in this report will be relevant to policy-makers, regulators, housing developers, social landlords and technical leaders within the housing industry.

The Elm Tree Mews housing scheme was originally conceived in 2005 by the Joseph Rowntree Housing Trust as a design and build competition called *21st Century Suburban Homes*. The aim of the competition was to build a small housing development on the site of a redundant used-car showroom in the New Earswick model village in York. The objective was to provide affordable, high-quality houses and flats both for sale and for rent. The dwellings had to meet the requirements of the JRF Lifetime Homes standard and reflect the aesthetics of the Arts and Crafts vernacular of the New Earswick village in general and the adjacent Folk Hall in particular. In addition, the development was intended to address the emerging low carbon housing agenda by achieving energy efficiency standards well in advance of the Building Regulations in force at the time (the Building Regulations, Part L, 2006).

The winning design for Elm Tree Mews was based on a panelised timber-frame construction system with cellulose insulation, a timber-clad and rendered façade and a tiled roof. The heating and hot water system was designed around a communal ground source heat pump in combination with solar thermal panels. The dwellings were designed to achieve an energy and carbon standard that is marginally short of that set subsequently as code level 4 in the Code for Sustainable Homes, 2006. The designed carbon emission rate is around 40 per cent lower than that required for dwellings constructed to the 2006 Building Regulations and is broadly in line with that anticipated for regulation in 2013. The low energy/carbon design at Elm Tree Mews relied on three key elements:

- high levels of fabric insulation and air tightness so as to minimise space heating demand;
- the use of a communal ground source heat pump to achieve very high levels of efficiency (a coefficient of performance of 3.2) in supplying space heating and hot water; and
- the installation of solar water heating to provide carbon free energy for about 30 per cent of hot water consumption.

The importance of projects like Elm Tree Mews lies in the challenges that the housing industry faces in relation to the regulatory framework for new housing over the next ten to fifteen years. The Government has set out ambitious targets for incremental changes to building regulatory standards that are intended

to achieve zero carbon new housing by 2016. Although design solutions exist for the construction of very low and zero carbon housing, there is considerable concern that many of these solutions are untried and untested within the context of mainstream housing production in the UK. Many schemes do not undergo comprehensive monitoring and evaluation to check whether the approaches chosen have achieved their designed performance targets. The Elm Tree Mews field trial was intended to begin to fill this gap in our understanding.

The Leeds Metropolitan University research programme ran from the spring of 2007 to the end of 2009 and included observations of the construction of the Elm Tree Mews development, post-construction measurement of fabric performance and air tightness, and monitoring of the dwellings for a year following occupation. A retrospective analysis of the procurement, design and construction processes was undertaken and interviews were carried out with key individuals involved in the development processes. Qualitative interviews were carried out with each household at the end of the monitoring period to capture the residents' experience of living in the dwellings and to understand the influence of user behaviour on energy and carbon performance. The research project constituted an exploratory case study, and although this will have its limitations, the detailed nature of the observations and quantitative and qualitative measurements undertaken, combined with a participatory action research approach, means that the insights and lessons from the project can be applied to the procurement, construction and operation of low and zero carbon housing more generally.

Actual performance

The performance of the dwelling envelope (insulation and air tightness) and the initial performance of heating and hot water systems were measured before occupation. This enabled the technical characteristics to be measured free from the variability introduced by different usage patterns. Following occupation, the dwellings were monitored over a twelve-month period, allowing the in-use efficiency of the dwelling and its systems to be established and the resident experience evaluated.

Fabric performance

Whole house heat loss is a combination of conduction, convection and radiation through the dwelling fabric (fabric loss) and via air leakage through small cracks in the structure (background ventilation loss). Whole house heat loss at Elm Tree Mews was much higher than predicted at design stage. Instead of a predicted total heat loss coefficient of about 127 W/K, the real loss was just over 196 W/K, giving an overall increase of some 54 per cent (70 W/K). Almost all of the additional loss was attributable to fabric losses, which means that, when compared with the predicted fabric loss, the discrepancy represented an increase of some 70 per cent.

Detailed investigations showed that the discrepancy was the result of design and construction process factors that:

- underestimated the amount of structural timber in the walls and roof, resulting in increased heat loss (23 per cent of the difference);
- did not account fully for thermal bridging at junctions, openings and other thermal anomalies (25 per cent);
- did not account for heat loss via a thermal bypass formed within the party wall cavities (30 per cent); and
- did not ensure that thermal performance was maintained when a change was made to the supply of windows during construction (21 per cent).

Air tightness

Pressurisation testing of the completed dwellings showed that air tightness was typical of current UK practice for mass housing, with a mean air permeability of 7 $m^3/(h.m^2)$ @ 50Pa, a figure well within the limiting maximum value of 10 $m^3/(h.m^2)$, required by the Building Regulations. The measured values were significantly above the target value of 3 $m^3/(h.m^2)$, which was contained in the original outline specification but not carried through into detailed design. The air permeability levels achieved were well above those that would be expected for a low energy housing scheme. Had the original target of 3 $m^3/(h.m^2)$ been achieved, the heat loss due to air leakage would have been some 50 per cent lower than the measured value.

Heating and hot water services

The communal ground source heat pump did not achieve its expected performance, with the measured annual Coefficient of Performance (CoP) of the pump of 2.7 being significantly lower than the nominal design CoP of between 3.2 and 3.5 (CoP is a measure of energy efficiency – a higher rate denotes greater efficiency). The annual CoP of the communal system as a whole was 2.15, after taking into account the performance of the heat pump unit, energy usage of the circulation pump, heat losses from the distribution system, and the control arrangements. A number of interventions were made during the monitoring period to improve the system efficiency. These included replacing one of the circulation pumps and altering the system controls.

The performance of the solar thermal systems also fell short of expectations, with a series of problems including leaks, control issues, incorrectly positioned sensors and flow restrictions in the pipe work. The design of the hot water system also raised concerns about the control of legionella bacteria due to the potential for low temperature water storage, and changes had to be made to introduce a weekly pasteurisation cycle. The various problems identified with the heat pump and hot water systems were related to design philosophy, the integration of the various systems in the initial design, and the robustness of the installation and commissioning processes.

In-use energy consumption and carbon emissions

The total annual electricity used by all the Elm Tree Mews dwellings for heating and hot water was around 15,000 kWh, equivalent to 6.4 tonnes CO_2/annum using the 2006 carbon coefficient for grid electricity (0.422 $kgCO_2$/kWh – a government estimate based on power station efficiencies, the mix of different generation fuels and transmission system characteristics). It is estimated that had fabric and systems performed as expected, electricity consumption would have been nearer 6,300 kWh, only 2.7 tonnes CO_2/annum. The extra carbon emitted as a result of fabric and services underperformance was therefore about 3.7 tonnes CO_2/annum. This figure would rise to 4.55 tonnes CO_2/annum under an updated national carbon coefficient for grid electricity (0.517 $kgCO_2$/kWh), due to come into force in October 2010.

The decision to use an electric heating system rather than gas placed considerable reliance on the performance of the communal heat pump. At the time the decision was made, the calculations supported the use of a heat pump system. However, the increased carbon coefficient of electricity coupled with lower than anticipated energy efficiency means that estimated emissions from a gas system would be about 1 tonne CO_2/annum less over the whole scheme. This illustrates the difficulties faced by designers and developers since they are often operating in the face of considerable uncertainty, having to contend with shifts in national carbon emission coefficients, the complex interplay between service efficiencies and fabric performance, and uncertainties about as-constructed performance. In order to address these issues it is important that:

- the Government provide a stable carbon emission coefficient platform rooted in robust long-term energy and carbon policy; and

- the house building industry tackle the considerable variability in as-constructed performance.

The resident experience

Resident interviews revealed a mixed experience, which was often related to individual circumstances and expectations. The key issues to emerge are as follows:

- **Affordability** Residents were generally pleased with the lower heating bills compared to their previous accommodation. One resident remarked that 'our last two bills [summer months], … which come to us monthly, one was £1.26 and the other was about £1.50 … I loved them, they're fantastic.'

- **Design and resident needs** Some important interactions between living needs and energy consumption emerged in relation to dwelling design. For example, one resident was considering using fan heaters to heat the winter garden (a type of conservatory with no heating) in winter to provide additional dining space. This could result in a significant increase in energy consumption and carbon emissions.

- **Engaging with new technologies** Controlling heating and hot water was complex, with four controllers (space heating, water heating, solar system and immersion heater), each with a different display and control button arrangement. Also, thermostat dials were difficult to understand. This complexity caused considerable confusion among residents. Controlling the supply of hot water was a particular area of difficulty.

- **Knowledge and confidence** The complexity of the systems meant that residents did not understand how they worked and did not have the confidence to make changes so as to find the best arrangement for their household.

Implications for the house-building industry

The evidence from Elm Tree Mews and other, similar projects suggests that underperformance is a common problem and that the underlying causes are a result of the cultures and processes that pervade the development of new housing, from master planning through design and construction, to our understanding of the needs of residents. It is therefore important to view the performance of Elm Tree Mews within the wider context of design and construction processes across the industry. The specific problems identified are indicative of much wider systemic problems relating to the way that housing is procured, designed and constructed in the UK.

Key lessons for the industry

Central to closing the performance gap is to improve the way homes are procured, designed and constructed so that they provide households with homes that meet their needs while ensuring low carbon emissions. The evaluation of Elm Tree Mews provides the following important lessons for the production of low carbon housing:

- **Procurement** Clients and customers need to take more interest in the energy and carbon performance of homes and in evaluating the extent to which designers and contractors/developers are able to provide objective evidence that claims made at the outset are achieved in practice.

- **Design** Design processes should be improved so that they:

- take a much more rigorous approach to detailed design including undertaking and checking thermal calculations,
- focus on as-constructed/as-installed performance taking into account the interactions of the different components in both fabric and services systems, and
- give more consideration to the needs of householders and provide controls that are designed in accordance with ergonomic principles.

- **Construction** Construction processes need to be improved so that:
  - construction operations and sequences are planned in more detail to ensure that one construction task does not hinder another and reduce performance,
  - changes during construction are more closely controlled to ensure that substituted products do not undermine performance, and
  - services commissioning is more robust, ensuring that expected efficiencies and other characteristics are being achieved from the outset.

- **The supply chain** Performance information and guidance provided by suppliers should be improved so that it reflects as-constructed/as-installed performance rather than laboratory performance. In the case of off-site construction systems in particular, the supplier should take more responsibility for energy and carbon performance.

- **Resident support** Developers and landlords should give more attention to the provision of meaningful guidance on the use and operation of the low carbon homes they provide. Social landlords are in a strong position to lead the way in this domain, providing feedback to designers and to developers on information requirements and the ergonomic design of systems and controls.

Feedback for continuous improvement

Performance feedback is vital if improvements are to take place. The Elm Tree Mews study should be seen as part of a continuing programme of feedback from real schemes that provide guidance for government and the industry as they seek to achieve national goals for low and zero carbon housing. An excellent example of the impact of feedback is provided by the results of a follow-up scheme developed by the Joseph Rowntree Housing Trust at Temple Avenue in York. In this case, the emerging results from Elm Tree Mews were used by the designers and contractors of the new scheme to make improvements to their processes. The performance of the follow-up scheme showed a marked improvement in whole house heat loss. Although a discrepancy in fabric heat loss still existed, it was much smaller (around 10 per cent to 15 per cent) than at Elm Tree Mews.

Implications for government

If national zero carbon housing goals are to be achieved, the performance gap identified in this scheme and elsewhere must be closed. There are encouraging signs that this is now being taken seriously by sections of industry and by government.

In recommending a way forward we propose a ten-year programme of radical change. The change programme should be developed and steered through a partnership consisting of government, industry and stakeholders. The key components should be based on a clear regulatory framework that is able to provide a high level of assurance that standards are being achieved in dwellings as-constructed. The regulatory system must encourage and support housing providers who invest in process improvement and meet required standards. At the same time it should be rigorous in identifying where standards are not met. The change programme would seek to develop industry processes, provide support through

a research and development programme, and through a programme of education and training to improve the skill base.

In addition to a process improvement programme, work should begin on the development of a national feedback loop that collects and analyses data on completed dwellings and their energy use. The national feedback should be capable of charting the performance of dwelling cohorts as the improvement programme develops and as regulations are modified, beginning with the 2010 regulatory change.

The objective of any compliance system should be to ensure that performance standards are met where it matters – on the ground. Elm Tree Mews has demonstrated many of the issues that need to be tackled in order to achieve the goals of zero carbon new housing. Important as the lessons are, it is vital that many more schemes are thoroughly evaluated along similar lines. However, in order to develop this learning process, the cooperation of clients, developers, designers, contractors and the supply chain will be of paramount importance. Equally, the participation of residents is vital. At Elm Tree Mews we were very fortunate. Without the vision and pioneering work of the design, construction and development team, and the forbearance of residents, there would have been nothing from which to learn, and no benefits to be gained. Those who strive to achieve high standards, subjecting their attempts to detailed evaluation, require the support and admiration of everyone who seeks a sustainable future.

1 Introduction

This report summarises the findings from the Elm Tree Mews low carbon housing field trial and discusses the broad lessons and policy implications for the development of low and zero carbon new housing. The research was undertaken by the Centre for the Built Environment (CeBE) at Leeds Metropolitan University. The research project was supported by the Joseph Rowntree Foundation (JRF) and undertaken in conjunction with the Joseph Rowntree Housing Trust (JRHT), who were the developers. The research was conducted between the spring of 2007 and the end of 2009.[1] During this period the research team was able to observe the later phases of construction, undertake post-construction measurement of fabric performance and monitor the performance in use of five of the six dwellings over a nine- to twelve-month period, depending on occupation dates.[2] In order to capture the performance of the scheme and the lessons it provides for the development of low carbon housing, the work is presented in two reports, each one aimed at overlapping but different audiences.

This final report for the Joseph Rowntree Foundation summarises the main technical findings and draws out the overall lessons and implications for policy and practice. The report is aimed at policy-makers, regulators, housing developers and technical leaders in the housing industry. It also provides an introduction to the technical and scientific findings.

A technical report (Wingfield, *et al.*, 2010) presents the results of the performance measurement and evaluation in more detail. The report covers detailed post-construction measurement, in-use monitoring of technical performance and the experience of dwelling residents. The technical report is intended primarily for those practitioners involved in the design and development of low and zero carbon housing and the technical and scientific community.

Designing and constructing any housing scheme is a very complex undertaking and performance has many aspects. The work reported here sought to address the issues of energy and carbon performance only. In order to provide context to the work other aspects of performance may be referred to, but in reading the report it is important to recognise that the research undertaken was not set up to evaluate those aspects of performance that do not relate to energy consumption and/or carbon emissions. Clearly, dwellings should perform in every respect and, very often, the art of good design lies in treading a difficult path between a complex array of requirements. However, energy and carbon performance has become much more critical in the last ten to twenty years and if low carbon housing is to become the norm, highly focused studies of the type undertaken here will become increasingly important alongside studies of other performance characteristics.

Background to the scheme

In February 2005, the Joseph Rowntree Foundation and the Housing Trust launched the *21st Century Suburban Homes* design and build competition for a small housing development on the site of a redundant used-car showroom (Elm Tree Garage) in the New Earswick model village in York (JRF, 2005). The site is adjacent to the grade 2 listed Folk Hall. The competition was inspired by the 100th anniversary of the 1905 Letchworth Cheap Cottages exhibition. The aim of the Elm Tree development was to provide affordable, high-quality houses and flats both for sale and for rent, all of which were to meet the JRF Lifetime Homes standard. The aesthetic requirements were focused on the need to reflect the Arts and Crafts vernacular of New Earswick in general, and that of the adjacent Folk Hall in particular. In addition, the

development was to address the emerging low carbon housing agenda by achieving energy efficiency standards well in advance of the Building Regulations in force at the time. The carbon standard that emerged in design was similar to that currently proposed as the regulatory target for the Building Regulations in 2013.[3] The carbon emission rate for the scheme, as designed, was around 50 per cent lower than the 2006 regulatory requirements under which the scheme was constructed, with a regulatory target rate in the region of 30 $kgCO_2/m^2.a$ as compared to a designed rate of around 15 $kgCO_2/m^2.a$.

The scheme was seen by the Housing Trust as providing valuable experience of the development of low carbon, high-quality sustainable housing, which was part of its longer-term development strategy. In particular it was expected that the development would provide practical ideas and technical data to support the design and construction process for a much larger development on the eastern fringe of York.[4] Four competition entries were short-listed and assessed against the competition criteria by a panel of independent experts.

Competition submission

An artist's impression of the design for Elm Tree Mews taken from the winning design submission is shown in Figure 1, set alongside the New Earswick Folk Hall. The final design was for a single block of six dwellings, which included four terraced houses and two flats. The steeply pitched roof and dormer windows of the proposed scheme echo the aesthetic of the adjacent Folk Hall.

In their competition submission, the designers state that past developments in which they were involved featured the use of intelligent and environmental features together with construction innovation, and a networking process of research and communication with stakeholders. The principles upon which the design was based are clearly articulated in the following quotation from the submission:

> *We believe that we meet users' needs by designing adaptable, low energy, low-maintenance homes that respond to orientation, views, sunlight and daylight, along with Lifetime Homes principles in their planning and details. By using off-site fabrication methods, and using standard component parts, we believe that we can produce excellent 'intelligent and green' dwellings which offer far better value, amenity and comfort than standard traditional construction and standard house plans. Costs can be brought down to the same level as traditional construction, if not lower, given sufficient numbers … Running costs are lower for energy, water and maintenance. Lifetime value is significantly greater. We*

Figure 1: Artist's impression of Elm Tree Mews from design submission and photograph of the adjacent New Earswick Folk Hall

have already provided various flagship demonstration schemes for Housing Associations and local councils, proving that high quality 'intelligent and green' homes can be affordable, attractive and can enhance neighbourhoods.

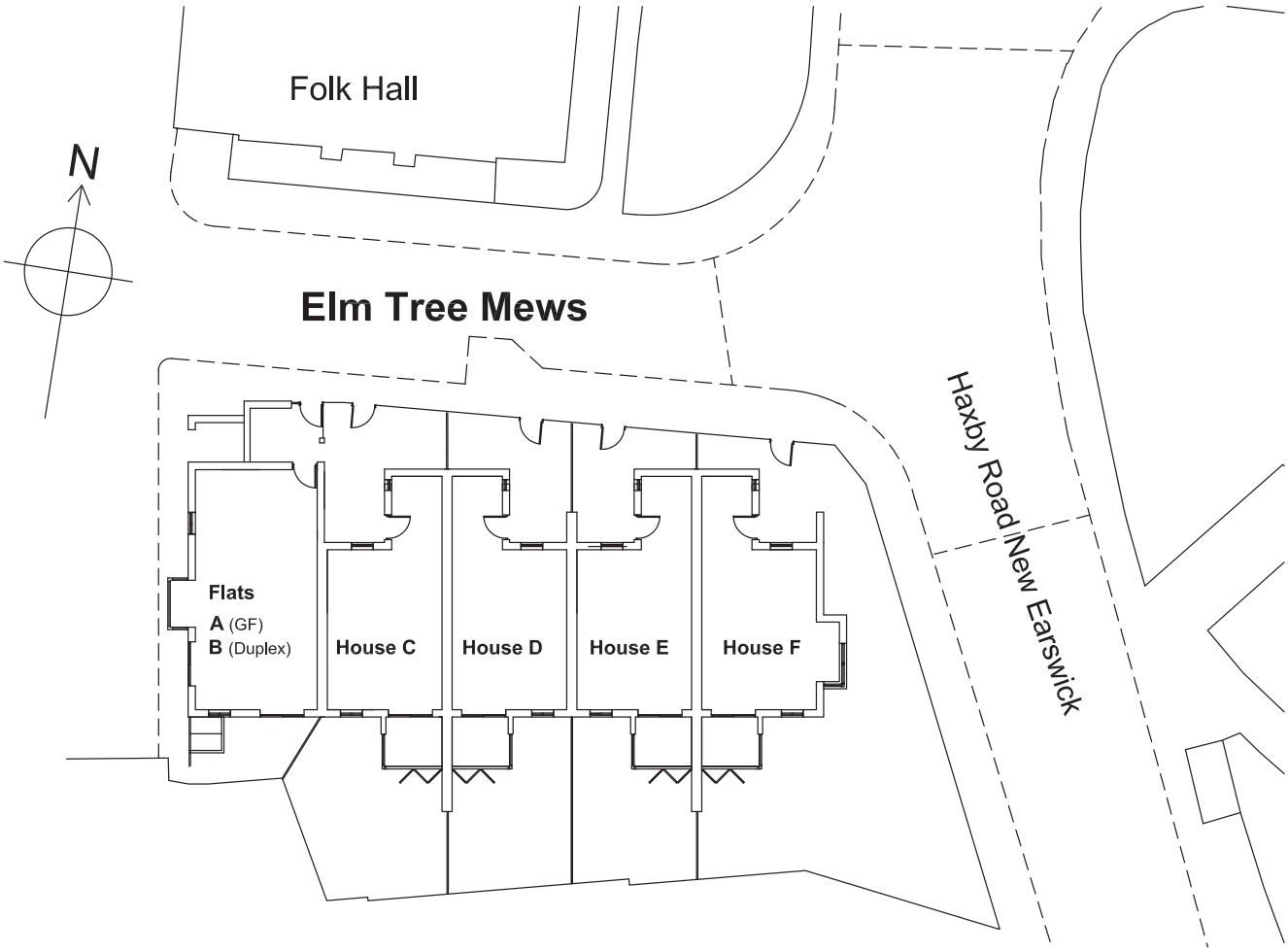
(Design Submission, 2005)

The general design approach of the successful submission was for a timber-clad/rendered timber-frame building with conventional gas-fired central heating, passive stack ventilation, solar thermal hot water and sunspace. The design targeted a base-level Ecohomes 'good' rating, which would be upgradeable to 'excellent' with the addition of options such as photovoltaic panels.[5] The building was designed with a south-facing façade and roof to maximise solar gain and efficiency of the solar collector and also to allow for possible future upgrading, such as photovoltaic panels. A mechanical ventilation system with heat recovery (MVHR) was suggested as an option but was discounted on the grounds of installation and maintenance cost.

Design development

During the detailed design phase, the design of the main building shell and layout of the dwellings remained largely unchanged. However, significant modifications were made to the space and water heating service. A heating options desk study was commissioned during 2006 (Watson and Hill, 2006) to assess the likely benefits from a ground source heat pump system in place of the traditional gas central heating system

Figure 2: Elm Tree Mews – site plan



originally proposed. This study concluded that there would be energy and carbon benefits from making the change and a communal ground source heat pump was specified.

The efficiency of heat pumps, which is usually referred to as a coefficient of performance (CoP), can be very high since they make use of low-grade solar energy source (ground, air, water, etc.), which is upgraded through the release of latent heat when a fluid in vapour form is compressed into its liquid state.[6] In effect, the electrical energy used to drive the heat pump compressor releases considerably more heat energy than the electricity input. This results in a CoP that can be much greater than 1 or, in percentage terms, over 100 per cent. The stated CoP of the communal heat pump at commissioning was quoted as 3.5 (350 per cent) but, in design calculations, a CoP of 3.2 (320 per cent) was used for delivered heat.[7]

Table 1: Description of final detailed design

Floor	Strip foundation with beam and block concrete floor with 90mm expanded polystyrene (EPS) insulation above, with nominal U-value 0.20 W/m^{2}K.
Main construction elements	Pre-insulated timber panels with cellulose insulation and orientated strand board (OSB) internal and external facings.
Wall panels	200mm deep pre-insulated timber I-beam panels with nominal U-value 0.18 W/m^{2}K. Internal wall lining 12.5mm plasterboard with service void. External rainscreen cladding with either timber boarding or rendered board.
Roof panels	240mm deep pre-insulated timber I-beam panels with nominal U-value 0.13 W/m^{2}K. Tiled roof.
Space heating system	24 kW 3-phase communal ground source heat pump with 300l buffer tank and nominal CoP 3.2. Heat pump located in plant room and connected to a district heating system. Underfloor heating system in individual dwellings connected to communal system. Ground source provided from three 115m deep bore holes. Zone control using zone thermostats and a programmable heating controller/thermostat.
Hot water system	Solar panels to twin coil unvented cylinders in dwellings with additional heat input from the communal heat main and electric immersion heaters. Systems used 1.3m^2 evacuated tube solar panels with 2 panels on the houses and 1 panel on the flats.
Air tightness	Nominal air permeability target given in SAP worksheet 10 m^3/(h.m^2) @ 50 Pa.
Ventilation	Natural ventilation with humidistat controlled extract fans in bathrooms and toilets and extractor hoods over cooker in kitchens.
Windows	Timber-frame double glazing with soft coat low-E coating. Nominal whole window U-value 1.5 W/m^{2}K.
Other design features	Single-storey solar sunspaces on south-facing façade.
Carbon emissions	End terrace: Dwelling Emission Rate (DER) 14 kgCO_2/m^2.a. Target Emission Rate (TER – electrically heated) 31.3 kgCO_2/m^2.a. By way of comparison the TER for a gas-heated dwelling of same size is 23.2 kgCO_2/m^2.a.

In order to maximise the efficiency gains of the heat pump, the space heat distribution system was redesigned within each dwelling using an underfloor heating system in place of radiators. The hot water system was modified from one supplied by solar thermal panels and gas boiler to a system that involved heat inputs from the solar thermal panels, the heat pump and a back-up electrical immersion heater. This change to the heating system meant that the dwellings used electricity as the only delivered energy source for heating and hot water. The passive stack ventilation system in the original design was replaced with a conventional intermittent extract system and trickle ventilators. Table 1 summarises the final design of the building fabric and services and Figure 2 illustrates the layout of the site and the terrace of dwellings.

Prior to commencing the detailed design phase, the design and construction team that had been proposed at competition stage was changed. The competition winning architect was retained but the main contractor, services engineer, quantity surveyor and other specialists were changed to include organisations local to the region.

Procurement timeline

The scheme was completed and the properties were occupied in June 2008, almost three and a half years after the design competition. Table 2 illustrates the development procurement timeline and Figure 3 shows the completed dwellings just before occupation. The procurement process included 20 months taken up by the competition and design development phases, 3 months' site decontamination

Table 2: Procurement timeline

Procurement stage	Date
21st Century Suburban Homes design competition announced	February 2005
Competition awarded	September 2005
Main contractor appointed	July 2006
Site remediation/decontamination works begun	November 2006
Foundation ground works begun	February 2007
Practical completion	March 2008
Building handover to JRF	May 2008
Occupation	June 2008

Figure 3: Elm Tree Mews – completed scheme

and 15 months from construction start to handover. The 15-month construction phase took more than twice as long as planned, with the original programme anticipating a 6- to 7-month construction period. This delay was caused, principally, by difficulties with the erection of the timber-frame panels, fitting of the roof and exposure to unusually heavy rainfall during June and July 2007. The impact of the rain on the unprotected structure meant that the closed panels had to be opened up, the insulation removed and the panels dried out before works could proceed. However, as reported below, the removal of the internal sheeting provided an opportunity for the research team to record the timber structure in some detail and assess its impact on thermal performance.

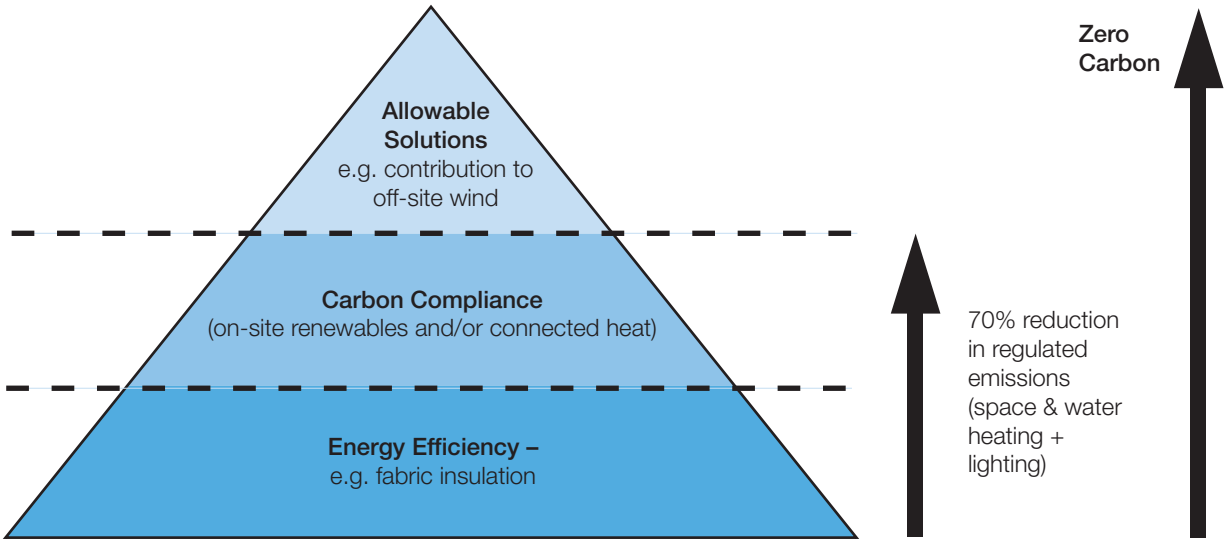
The policy environment

Elm Tree Mews was conceived in order to tackle a number of improvements in housing for the 21st century. However, the research project focused on measures that sought to address the emerging zero carbon housing agenda. In December 2006, shortly before construction began, the Government produced their green paper *Building a Greener Future* (CLG, 2006a) and the first edition of the *Code for Sustainable Homes* (CLG, 2006b). The green paper was revolutionary in proposing that all new housing, post-2016, would have to achieve a net carbon emission rate of zero. The proposed zero carbon policy was to include emissions from appliances such as washing machines, televisions and fridges as well as those normally regulated through the Building Regulations (space and water heating and lighting).[8] The paper also set out a programme of regulatory change that would require carbon emission reductions (based on the 2006 regulatory standard) of 25 per cent in 2010 and 44 per cent in 2013, with the final shift to zero carbon three years later. Following consultation, the proposals were formally adopted in a ministerial statement in July 2007 (CLG, 2007a), and the first regulatory change (25 per cent reduction) is due to come into force in October 2010. The original definition of zero carbon lacked clarity and did not acknowledge issues of technical feasibility, particularly on urban sites where achieving site-based solutions would be difficult. Subsequent work by the Zero Carbon Hub and Department for Communities and Local Government (CLG) resulted in a consultation document on the definition of zero carbon (CLG, 2008b). Figure 4 shows the Government's preferred hierarchy in which zero carbon would be demonstrated, firstly by a minimum level of energy efficiency, secondly by on-site renewables and lastly by allowable solutions against which residual carbon emissions can be offset.

The first two levels in the hierarchy constitute a minimum level of carbon compliance that will have to be met for each dwelling on a development. The appropriate minimum level for each dwelling is defined as a 70 per cent reduction in emissions attributable to space and water heating and lighting (regulated emissions). The base line for the 70 per cent reduction is set by the 2006 edition of Part L of the Building Regulations for England and Wales.[9] The third level (allowable solutions) provides an option for developers to offset any remaining carbon emissions by off-site means such as making a financial contribution to a large wind farm. This means that about 50 per cent of total emissions could be accounted for by offsetting and 50 per cent by building and site design (insulation, fuel efficiency and on-site energy generation). The improvement in regulated emissions achieved by the final design at Elm Tree Mews amounted to a reduction of around 40 per cent when compared with the 2006 Building Regulations (gas-heated base case). This equates to a Dwelling Emission Rate (DER) that is marginally above the 44 per cent reduction proposed for regulation in 2013.

Since 2007 the Zero Carbon Housing policy has been reinforced by a similar target for non-domestic buildings constructed post-2019 (CLG, 2009d). The intensification of the policy environment during the construction of Elm Tree Mews has increased the importance of the scheme and the learning it provides for the design and construction of low and zero carbon housing. Elm Tree Mews is not the first scheme in the UK to be designed to low carbon standards, and the number of exemplar schemes is increasing. However, the significance of Elm Tree Mews lies in the extent of performance measurement, forensic examination and evaluation it has undergone.

Figure 4: Hierarchy of compliance with zero carbon homes (after CLG, 2008b)



Evidence has been mounting for some time that the realised energy and carbon performance of new dwellings in the UK is unlikely to match that defined by regulation or design calculations. The Stamford Brook project (Wingfield, *et al.*, 2008) studied the energy performance of a commercial development of around 700 dwellings designed in 2001 to a standard about 10 per cent in advance of the 2006 regulations (code level 1). This project was the most comprehensive housing field trial to be undertaken in the UK in the last 20 years and demonstrated that heat loss could be more than double that predicted. It also identified underperformance in heating system efficiencies and other aspects of services design and construction. The combined impact of higher heat loss and lower system efficiencies in the dwellings measured increased overall carbon emissions by close to 25 per cent. Other studies of whole house heat loss have shown a similar picture for dwellings constructed to 2006 standards (Wingfield, *et al.*, 2009) and for a demonstration dwelling designed to Code for Sustainable Homes level 5 (Stevenson and Rijal, 2008).[10]

Concerns within government and the industry about the carbon and energy performance of new build housing (and retrofitting of the existing stock) are increasing. A National Audit Office report in November 2008 (NAO, 2008) and a Public Accounts Committee report in 2009 (House of Commons Public Accounts Committee, 2009) highlighted issues regarding non-compliance and underperformance. In addition, the consultation document on the proposed changes to Part L of the Building Regulations devoted a whole chapter to the problem and ways in which compliance could be improved (CLG, 2009b). Given the intensification of government policy on carbon emissions from dwellings, the evidence on energy and carbon performance and the very short timescales involved, it is vital that the lessons from Elm Tree Mews are disseminated widely. However, it must be acknowledged that Elm Tree Mews is only one scheme adopting one of a number of different approaches to low carbon design and construction. If learning is to continue and zero carbon standards are to be achieved across house building in general, it will be necessary to measure and evaluate many more schemes covering a wide range of technologies and approaches to compliance.

Since the adoption of the zero carbon housing targets and the regulatory trajectory in 2007 (CLG, 2007a), a number of developments, have been planned, such as those under the Carbon Challenge programme (English Partnerships, 2007) that seek to pilot zero carbon housing standards. An important example of such a pilot scheme is the Homes and Communities Agency Hanham Hall development near

Bristol (HCA, 2008), which began construction in late 2009. Important though such pilot developments are, the nature and extent of measurement and evaluation programmes remain very unclear. The work at Stamford Brook (Wingfield, *et al.*, 2008) and at Elm Tree Mews would suggest that the extent of detail and the level of forensic investigation required are considerable. Also, there are significant barriers to publishing what can sometimes be interpreted as failures on the part of the actors involved. As one of the first low carbon schemes to be subjected to detailed investigation Elm Tree Mews is in a position to provide insights not only into the technological and process issues but also into the nature of the research and evaluation required to learn from and apply the lessons to future pilot developments and, ultimately, to mainstream house building.

Research objectives

The broad aim of the proposed research project was to evaluate the extent to which the actual performance of low carbon energy housing meets that specified at design stage. Another objective was to understand as much as possible the factors that contribute to the performance observed, including the resident experience and the way that people interact with their home. Despite the fact that design solutions exist for the construction of very low and zero carbon housing, there is considerable concern that many of these solutions are untried and untested within the context of mainstream housing production in the UK. It is also clear that many schemes do not undergo comprehensive monitoring and evaluation to check whether the approaches chosen have achieved their designed performance targets. This research project was designed to begin the process of filling this gap in our understanding.

This aim was pursued through a review of design and construction records, measurement and monitoring of physical performance, and the relationship between the residents and their home. As such, the project was an exploratory case study and although the normal limitations of such an approach apply, the depth and richness of the data obtained were considerable. In the medium to long term the study should be seen as part of a canon of low carbon housing field trial case studies that will chart the progress made towards low carbon housing and point the way to achieving zero carbon housing in mass production.

The broad aim was supported by the following sub-objectives:

- To evaluate energy and carbon performance as predicted at the design stage including a review of the information and approaches used by the design and construction teams.

- To assess, retrospectively, the procurement process in general and the key design and construction decisions in particular.

- To observe the latter stages of the construction and to review retrospectively any available construction records so as to provide as clear a picture as possible of what was actually constructed. Such observations are crucial to the interpretation of measurements taken upon completion.

- To undertake post-construction (pre-occupation) measurements of the performance of the dwelling fabric and to make an initial assessment of the commissioned heating and hot water services. This is primarily concerned with the extent to which measured heat losses, through both air leakage and direct heat transfer through the external envelope, are in line with those predicted at the design stage.

- To undertake monitoring of energy and carbon performance during occupation, including the performance of services systems and the physical internal conditions achieved.

- To evaluate the experience of residents, in terms of their feelings about their home, the levels of comfort achieved, their energy expenditure and their experiences in controlling their home so as to meet their lifestyle needs.

In pulling together the vast amount of both quantitative and qualitative data, the research team sought to understand not only the physical interactions at work but also the impact of the processes that were adopted throughout the whole development phase and the extent to which residents were able to make effective use of their homes. Although the insights gained into the various technological factors were expected to provide an important contribution to technical understanding, it is the insights provided into design and production processes that are most likely to improve the ability of the industry to produce zero carbon housing that is robust and reliable.

2 Approach to scheme evaluation

The development of any housing scheme is a complex undertaking. To construct to a standard that few developments have sought to achieve not only increases the complexity of the process but also requires a considerable amount of learning, much of which has to take place under intense time and cost pressures. In addition to the pressures of time and cost, design and construction teams often have to operate in the face of considerable uncertainty. Even in relatively routine developments, designers and constructors have to reconcile a wide range of factors and meet an increasing array of design standards, such as secured by design (ACPO, 2010) and lifetime homes (CLG, 2008d; Habinteg, 2010) as well as the code for sustainable homes (CLG, 2008a), which covers eight different aspects of sustainability in addition to energy and carbon emissions. To do this they rely on the supply of information from a wide variety of sources. The information provided has to be interpreted and tailored so that it can be applied effectively in the particular circumstances of the scheme. When it comes to low carbon housing, the level of uncertainty increases markedly and considerable skill is required to navigate the labyrinth of standards and their different information needs. To borrow from that classic definition of design by Chris Jones, the process amounts to a 'complicated act of faith' (Jones, 1970).

Given the importance of understanding the complexity of the undertaking, simply measuring energy and carbon performance in isolation would not deliver the understanding sought. As a consequence, the research project adopted an approach rooted in the participatory action research tradition, rather than one of detached measurement and observation (Greenwood, *et al.*, 1993). Indeed, it is difficult to envisage a research project such as Elm Tree Mews that did not involve such an approach. However, the opportunity to become immersed in all aspects of the procurement process was limited since the timing of the research project precluded full involvement in all stages of the procurement process.[11] To some extent this limitation was mitigated by conducting a retrospective study based on qualitative interviews with key actors, further exploration of process in response to the specific measurements/observations made and a continual review of design and procurement documentation such as the competition submission and the heating options report (Watson and Hill, 2006). The lack of direct participation in formative processes was less marked in the construction phase where there was an opportunity to observe, at first hand, the difficulties that resulted in construction delay, the details of the construction of the superstructure and the installation of the services.

The Action Research tradition, with its focus on process and on the flexibility it affords to researchers to work within the system they are studying, is well suited to the sort of learning that needs to be teased out of pilot schemes such as Elm Tree Mews. The insights gained into process and into the 'why' as well as the 'what' of energy and carbon performance stem largely from researcher participation in the development team and the mutual respect and personal relationships that are developed. Such a close relationship also enabled discussion of issues as they arose, a factor that provided a two-way feedback mechanism and deepened the learning of both research and development teams. Also, it enabled improvements to be put in place to deal with problems as part of the process. However, as discussed in the final section of this chapter, this is not without its dangers since to measure performance will always run the risk of delivering disappointment and, in an industry that is prone to dispute, a search for blame. Addressing this problem requires considerable skill and not a little fortitude on the part of all those involved in the scheme.

Understanding design and construction

The involvement of the research team began formally in January 2008, but from as early as the beginning of March 2007 the research team was gathering data during the construction phase. These early construction observations proved to be valuable when it came to interpreting the heat loss measurements (see Chapter 3). On other occasions the research team was able, from monitoring data, to identify areas where improvements could be made, particularly in services installations. The constant interplay between observations and modification works was particularly useful in providing insights into design and construction processes.

Design and designed performance

As indicated above, by the time the research project began the design phase was substantially complete. In order to understand the design and procurement processes and the expected performance of the scheme, the research team had to rely on a retrospective approach. This consisted of the following main elements (further details are contained in the technical report):

- **Design documentation review** A review of design documentation was undertaken that involved not only drawings, specifications and energy modelling, but as much of the design correspondence and meeting notes as were available.[12] The review also included the competition material, competition submission and reports relating to the consideration of heating and hot water services options. Wherever possible, the design calculations were checked for consistency and compared with calculations undertaken by the research team.

- **Interviews with development team members** In order to improve understanding of the design process and to fill out background information and other material that could not be gleaned from direct involvement by the research team, a series of semi-structured interviews were carried out with key members of the development team. Six interviews were undertaken, three with members of the client team, two with the contractor's management team and one with the building services and energy consultant. Unfortunately, it was not possible to conduct interviews with the design team.

- **Construction observations** The involvement of the research team during the latter part of the construction phase and their involvement in monitoring post-occupation provided additional insight into the design process. Much of this resulted from observations of fabric construction and services installation, which prompted design-related questions. The observation process provided informal information channels involving some suppliers and subcontractors who were not formally interviewed.

The design documentation provided a clear picture of the design intentions and the interviews supplied important material on the higher-level design and procurement process. However, the research programme was not able to incorporate investigation of the more detailed levels of design. In most building projects a substantial part of the detailed design is in the hands of specialist suppliers and subcontractors who are provided with a performance specification. Although a number of the difficulties observed during monitoring often shed light on related issues, it was not possible to undertake a systematic and comprehensive analysis of the detailed design processes undertaken by specialist subcontractors and suppliers.

Construction

The construction phase of the scheme was captured through a series of photographs, site observation notes, informal discussions and project management correspondence. Prior to formal commencement of the research project at the beginning of January 2008, the research team made a number of visits between March and December 2007 to photograph and note the construction as the scheme was built. Some nine visits were made up to December 2007 and followed up with a further twenty-seven between January and June 2008 as dwellings were completed.

One of the most important visits took place in August 2007, following the stripping of the internal face of the insulated timber panels and removal of the water-damaged insulation. This provided an ideal opportunity to observe the internal structure of the panels. At this visit a series of panoramic (360°) photographs were taken. Figure 5 illustrates how the photographs were taken and shows the state of the interior of the construction at the time. During the same visit a measured survey of one section of the ground floor was carried out so as to provide a direct measure of timber elements and their arrangement. The photographic data was used to estimate the proportion of solid timber (timber fraction) within the insulated frames, a number that is important in heat loss calculations.[13]

The photographic record of construction was used on a considerable number of occasions to assist in the interpretation of post-construction measurement and in-use monitoring results. Examples included the use of photographs of the ground floor construction and the party wall construction to assess a thermal bypass identified in the party walls and to pinpoint the likely location of a pipe-work defect in the solar water heating system.

Measuring energy and carbon performance

In seeking to understand energy performance, it is important to distinguish between the influence of the dwelling fabric and services, and that which can be attributed to the patterns of occupancy and the lifestyles of residents. It has long been observed that energy consumption can vary considerably from one household to another even when living in houses with similar physical attributes. Sonderegger's study (1978) of space heating energy use where change in occupancy had occurred (movers) compared with dwellings where no occupancy change took place (stayers) concluded that consumptions for space heating can vary by 100 per cent or more as a result of occupancy and behaviour factors alone. Based

Figure 5: Observations during site visit on 31 August 2007

Taking panoramic photographs

Internal panel structure showing additional timber, particularly around openings

on such evidence it is common for variations between design expectations and actual consumption to be explained in terms of usage rather than the performance of fabric and services. However, it is clear from work on fabric and services performance (Wingfield, *et al.*, 2008; Hens, *et al.*, 2007; Orr, *et al.*, 2009) that this general assumption cannot be made. Indeed, measurements of whole house heat loss can give rise to variations at least as large as those associated with use and behaviour.[14]

In order to enable the performance of the dwelling fabric and services to be disentangled from the performance of the dwellings in use, the measurement at Elm Tree Mews was conducted in two phases. The first sought to measure the performance of the dwelling fabric post-construction and prior to occupation. The second phase consisted of a more conventional in-use monitoring programme over a twelve-month period, which was designed to establish the performance of services and to explore usage issues and resident experience in general.

Post-construction measurement

The objective of the post-construction measurement phase was to establish the whole dwelling heat loss characteristics of the fabric and the contribution to the total of the different heat loss mechanisms. Also, preliminary observations were made of the initial performance of the heating system and the solar hot water system. The fabric measurements obtained were compared with those predicted at design stage.

Air tightness

An important element in dwelling heat loss is through air exchange between inside and outside. Some air exchange is necessary in order to provide adequate ventilation, however it is important that this is controlled through a well-designed ventilation system. Much of the leakage through the fabric is uncontrolled and is often additional to designed ventilation. In most cases the net result will be an unnecessary increase in heat loss. For this reason, the 2006 edition of the Building Regulations set a maximum air leakage level and required some limited testing to be undertaken.

In order to assess the air tightness of the external envelope of the dwellings, pressurisation tests were undertaken in all dwellings and carried out in accordance with the standard methods used for Building Regulations compliance (ATTMA, 2007). The test result is usually quoted as an air permeability, which has units of m^3 (internal volume) per m^2 (internal envelope area) per hour at an elevated standard test pressure of 50 Pascals ($m^3/(m^2.h)$@50Pa). The test result is used in the SAP model to derive an average background leakage rate over the heating season, which is combined with losses from the designed ventilation system to derive the total ventilation heat loss element. The photographs in Figure 6 show a pressure test in progress.

In addition to deriving a measure of dwelling air tightness, each pressurisation test was used to undertake a leakage detection survey using smoke generators. Figure 6 illustrates the approach to leakage detection using smoke to identify leakage paths. However, it is important to note that such surveys provide a qualitative picture of potential leakage paths since they are only able to show where air is leaking into or out of the construction at the internal surface. Air paths to the outside often involve a complex network of routes as air travels through cavities within the construction, such as internal partitions and floor voids.

Whole dwelling heat loss

Whole dwelling heat loss was measured in the end terrace house (House F, see Figure 2), using a coheating test methodology (Wingfield, *et al.*, 2008).[15] The test was conducted in the end terrace house during the period of 25 February to 12 March 2008. External weather data during the period of the coheating test (external temperature/humidity, vertical south-facing solar insolation, wind speed/direction) were recorded by a weather station installed by the research team, which was located 500m away, on the side of a building

Figure 6: Air tightness testing and air leakage detection

Pressurisation equipment fitted in the front door opening – internal view showing fan and controller

Air leakage detection recessed light fitting using hand-held smoke generator

at the Joseph Rowntree Housing Trust works depot. The internal temperature during the coheating test was maintained at around 25°C with the heat provided by electric fan heaters and air mixing provided by circulation fans. The temperature of the adjacent mid-terrace was also measured and maintained at an elevated temperature of between 20 and 25°C in order to minimise heat flux across the party wall from the coheating test house. However, this temperature, although monitored, was not controlled by the research team.[16] Energy input to the dwelling during the coheating test was recorded using kWh meters on each floor connected to the fan heaters, circulation fans and auxiliary test and data-logging equipment.

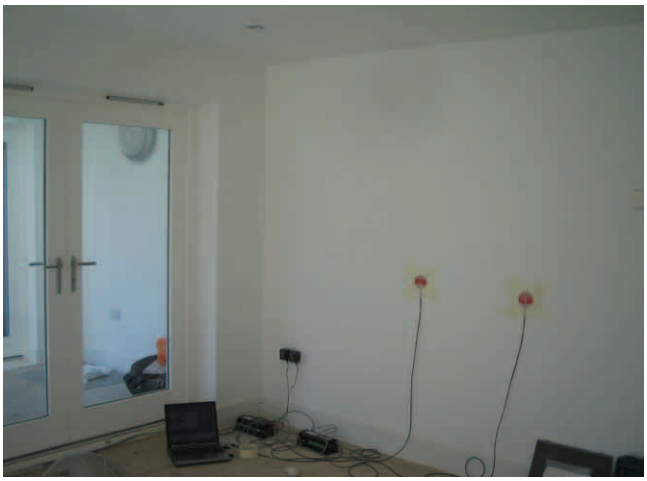
In order to enable more detailed investigation of the measured result, additional measurements were taken during the coheating test, including temperatures in the party wall cavity (at three positions), heat flux through various construction elements (flux sensor positions changed during the coheating test) and carbon dioxide concentration (on the ground floor and top floor). Qualitative data in the form of thermal images was also collected during the test to help identify any construction anomalies and assist in backtracking through construction photographs. Figure 7 illustrates the main test equipment set up and additional heat flux measurements undertaken. A full description of the methods adopted is given in the technical report (Wingfield, *et al.*, 2010).

Forensic examination

Throughout the post-construction evaluation, attempts were made not only to measure the performance ('the what') but also to understand the technological and other factors that contributed to the performance observed ('the why'). This forensic approach provided qualitative depth to the investigation and acted as a triangulation of some of the measured results. The examination was done through a combination of the review of design information, construction site visits and photographs, and additional measurements such as heat flux and thermal imaging.

Figure 7: Whole house heat loss measurement equipment

Main test equipment – showing heater, circulation fan and temperature control



Heat flux sensors attached to the party wall

Figure 8 illustrates the use of thermal imaging in identifying likely hidden airflow paths within the construction. In the case illustrated, the air leakage around the electrical services entry point is very clear from the colder areas that result from cold air being sucked into the construction during a depressurisation pressure test.

Throughout the project, attempts were made to reconcile the measured physical data with the qualitative observations from design, construction and occupation. For example, it was possible to use observations of the timber panels and of the size of the party wall bypass to close the 'loop' and reconcile the measured whole house heat loss with calculations based on construction observations rather than design assumptions. A similar approach was taken to understanding the relationships between measured and modelled annual energy consumption.

Commissioning and pre-occupation measurements of systems performance

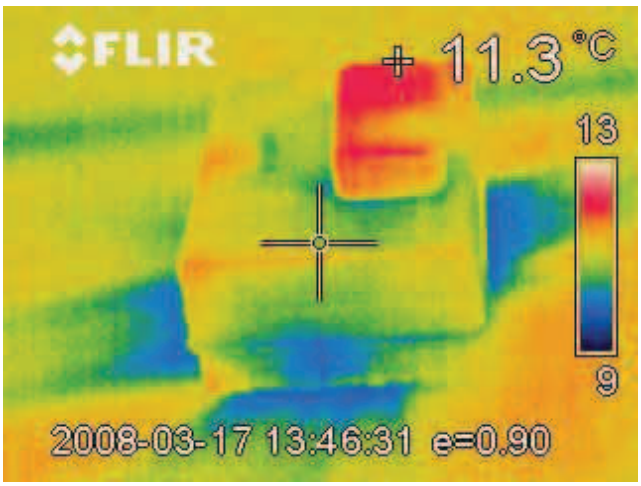
Following handover of the completed dwellings in May 2008, the heat pump system and solar thermal systems were left running. This provided an opportunity to take manual readings of heat meters and electricity meters prior to occupation and to inspect commissioning procedures. Readings of heat pump inputs and outputs were undertaken from 2 May to 26 June 2008, during which time a number of problems were identified and some modifications made. Similarly, manual meter readings of heat meters in the unoccupied dwellings raised a number of questions over the operation of the solar water heating systems. Indeed, the problems with the solar systems precipitated a short monitoring study (from 11 to 17 June 2008) in which existing monitoring equipment together with additional equipment was used to compare the performance between two of the dwellings (see the technical report, Wingfield, *et al.*, 2010). As with the heat pump installation, this revealed a number of problems that required rectification works. As far as possible, the research team sought to obtain commissioning certificates for all systems. Commissioning certificates were obtained for the ground source heat pump and the solar hot water systems.

Post-occupation monitoring

Monitoring of occupied dwellings was carried out in all but the end terrace dwelling, which was fitted out as a show house and not occupied. The other dwellings were either tenanted or were in shared ownership. The objective of post-occupation monitoring was to measure and evaluate the performance of space

Figure 8: Use of thermal imaging to assess air infiltration paths

Electricity entry point



Cold air infiltration cooling the area around the electricity entry point

and water heating services, energy consumption (disaggregated by source), internal conditions and the experience of the residents and their approach to using their home. Monitoring and data recording were done with the use of wireless sensors/transmitters sending data to a data logger situated in the communal plant room. A modem connection enabled remote downloading of data, which was done on a two- to three-day basis, depending on circumstances. Table 3 sets out the physical characteristics that were monitored in each dwelling and in the plant room.

In addition to the standard monitoring, additional measurements were undertaken for short periods in order to understand anomalies that became evident with particular systems during the course of the ongoing data analysis. This was the case, particularly in the first few months of operation, where investigation of the heat pump installation and the solar water heating systems required additional measurements of such things as water temperatures, control set points and electricity to the solar circulation pump. These one-off measurements resulted in rectification works and some modification works designed to improve performance. This included repairing solar pipe work to remove flow restrictions caused by kinked pipe work in two of the dwellings and improving the control and pumping arrangements of the heat pump system. In all cases, the interventions were noted so as to enable effective interpretation of the monitoring data.

The resident experience was evaluated primarily from qualitative interviews conducted at the end of the monitoring period in September 2009. However, during the monitoring period there was considerable informal contact between the research team and the residents. Much of this was precipitated by problems with the installation of some of the services and operation of the new and unfamiliar systems. Since this informal contact was often the result of assistance provided to residents, the record consists principally of correspondence between the research team and JRHT on the issues raised and assistance provided. Indeed, this contact with respect to the existence of 'teething troubles' was responsible for a decision not to conduct interim interviews, as had been planned. The information gleaned during this period was valuable in helping to understand some of the issues that arise with the application of new and unfamiliar systems.

Table 3: Monitoring arrangements

Monitoring elements	Description of measurement
Space heating system – communal ground source heat pump (GSHP) and distribution system	**Energy input:** Electricity to GSHP (including internal water pumps for ground loop and hot-side circulation to buffer tank), heat main circulation pump and buffer tank auxiliary immersion heaters. **Energy output:** Heat from GSHP to buffer tank and heat main, heat to dwellings (space heating in each dwelling by subtraction of communal heat to domestic hot water). **Temperatures:** Flow and return GSHP to buffer tank, flow and return buffer tank to heat main, flow and return to ground source (bore holes), ground temperature at 1.5m, buffer tank. **Control:** Communal system control settings and qualitative assessment of control strategy.
Water heating system, GSHP, solar, immersion heater	**Energy input:** Electricity to dwelling immersion heaters, heat input from solar thermal panels and heat input from GSHP heating system to each dwelling and to hot water storage cylinders. **Hot water consumption:** Volume of hot water used (flow meter on cold feed to cylinder). **Control:** Qualitative assessment of control strategy for different heat inputs.
Lights and appliances	**Energy input:** Electricity to the whole dwelling (less electricity to immersion heater).
Internal conditions and resident control	**Temperature and humidity:** Five locations throughout the dwelling (living room, hall or adjacent WC, kitchen, master bedroom, other bedroom). **Carbon dioxide:** One location – kitchen or bedroom. **Resident control:** Qualitative assessment of control set points and use of systems controller (timers and thermostats), observations of window opening. All assessed from final interviews and informal observation during visits over the monitoring period.

3 Post-construction performance

The objective of the post-construction phase measurements was to establish, as far as possible, the physical characteristics of the dwelling that residents are provided with and in which they will make their home. The starting point for almost all low carbon dwellings is the design and construction of a well-insulated and air tight thermal envelope into which is built efficient and controllable mechanical and electrical services. Together, the fabric of the building and its services (space and water heating, lighting, ventilation, etc.) provide the backdrop against which people live their lives and, in the process, make use of energy and emit carbon. The consumption of energy in homes is the result of a complex set of interactions not only between occupants and the fabric and services but also with each other and with an increasing range of energy consuming appliances. However, understanding the physical performance of the fabric and services, before occupation, is fundamental to being able to unpick some of the complex interactions that take place in use and their energy and carbon consequences.

Since 2006 all new dwellings in England and Wales have had to achieve a maximum carbon emission rate as calculated by the Standard Assessment Procedure (SAP, DEFRA, 2005).[17] The SAP model adopts standardised usage characteristics, which are coupled with the physical characteristics of the fabric and services to produce an estimate of annual energy consumption and carbon emissions. In this report, considerable reference is made to SAP as a point of comparison. However, in making comparisons it is important to distinguish between those that relate to the physical characteristics of the dwelling fabric and services and those that relate to usage patterns. In this chapter we seek to provide a summary of the physical performance of the dwellings as-constructed. A more detailed treatment of the post-construction performance is provided in the companion technical report (Wingfield, *et al.*, 2010).

Designed energy performance of fabric and services

The low energy design at Elm Tree Mews relied on three key elements:

- **High levels of fabric insulation and air tightness** to reduce space heating demand to as low a level as possible.
- **The use of a communal ground source heat pump** to achieve very high levels of efficiency (a CoP of 3.2) in supplying heat for space heating and hot water.
- **The installation of solar water heating** to provide carbon free energy for about 30 per cent of hot water consumption.

This chapter compares the performance of the dwellings as-constructed with design predictions. However, design predictions can vary depending on the point at which design is said to be complete. In order to establish a consistent approach, the analysis is based on the final design as presented in the 'as-constructed' Building Regulations submission, supplemented by the measured air tightness values obtained upon completion.

Measured fabric performance

Fabric heat loss

Fabric performance was determined from air pressurisation tests on all dwellings, a coheating test on the end-terrace dwelling and additional measurements of heat flux and other physical properties during the test. The most striking result of the fabric heat loss measurements was the large discrepancy between the designed heat loss from the dwellings and that measured by the coheating test prior to occupation. This discrepancy is illustrated in Figure 9, which shows a difference of just under 70 W/K (54 per cent) between the design prediction (127.5 W/K) and the measured value. The value derived from the test data includes both the heat loss associated with background air leakage (background ventilation loss), which excludes in-use ventilation loss, and heat transmission through the construction and its insulation (fabric loss). However, since the predicted value in Figure 9 is derived from field measurements of background air leakage, most of the difference can be attributed to direct heat loss through the thermal envelope (fabric loss). This being the case, if one compares the measured value (169.8 W/K) with the design fabric loss (100.9 W/K) the proportional discrepancy is just under 70 per cent.

Forensic examination of heat loss (see the technical report, Wingfield, *et al.*, 2010) identified the following critical factors:

- **Wall U-value** The calculation of wall U-values underestimated by a considerable margin the amount of timber that penetrated the insulation layer. Measurements made from panoramic photographs (see Figure 5 and Figure 10) indicated that some 25 per cent of the opaque wall area was taken up by solid timber (timber fraction) and the remaining 75 per cent was insulation (Ward, 2008). This contrasts with a value for the timber fraction of only 2.5 per cent used in design calculations. The net effect was that the U-value increased from 0.18 W/m^{2}K to 0.3 W/m^{2}K, an increase of over 65 per cent. The as-constructed wall U-value estimate of 0.3 W/m^{2}K was supported by heat flux measurement during the coheating test.

Figure 9: Coheating data – power versus internal and external temperature difference (Delta-T)[18]

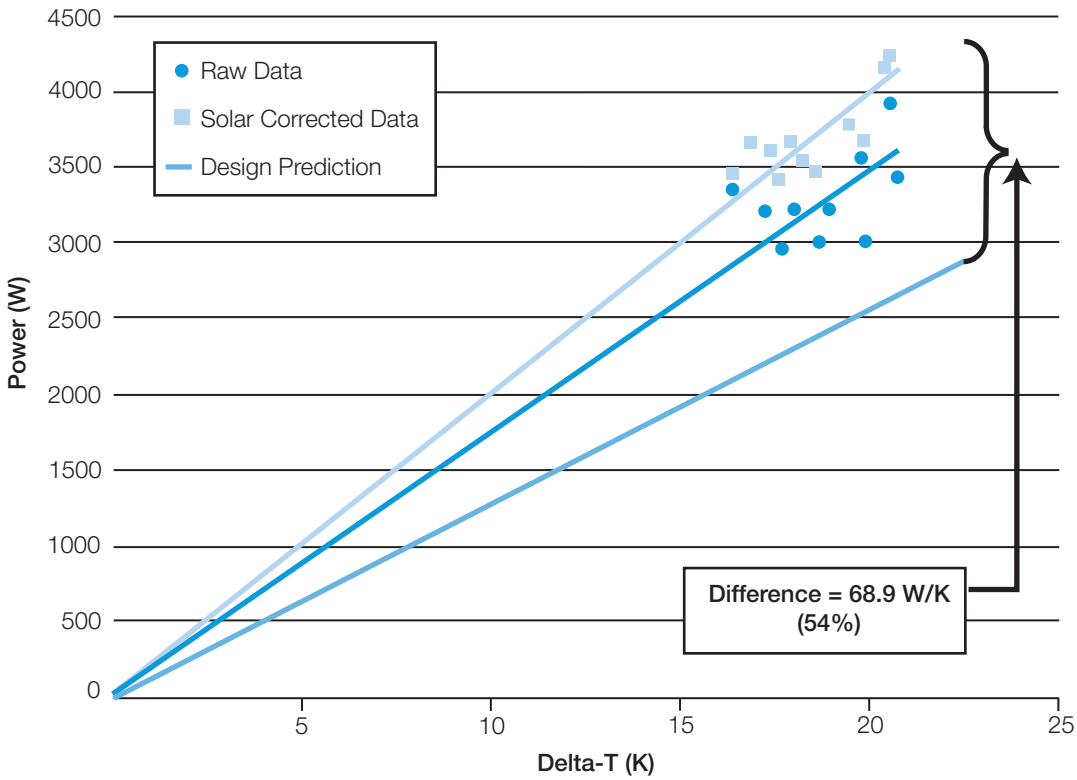


Figure 10: Screen capture from panoramic of gable wall section in House F

- **Roof U-value** Although not as marked as in the walls, similar issues of timber fraction also existed in the roof construction (see Figure 11) where construction observations suggested that the actual U-value was in the region of 0.18 W/m^{2}K instead of the 0.13 W/m^{2}K assumed in design.

- **Product substitution** The substitution of locally sourced double glazed windows for those specified during detailed design resulted in an increase in whole window U-value from 1.5 W/m^{2}K to around 2.0 W/m^{2}K.

- **Thermal bypassing** Heat flux and other measurements conducted during the coheating test provided evidence of a thermal bypass within the party wall cavity.[19] This heat loss mechanism was not recognised at the time the design was completed and has only recently been incorporated into the

Figure 11: Additional timbers in roof panels

Building Regulations. However, the effect of the bypass was to change the U-value of the party wall from the conventional assumption of zero to a value of around 0.3 W/m²K.[20]

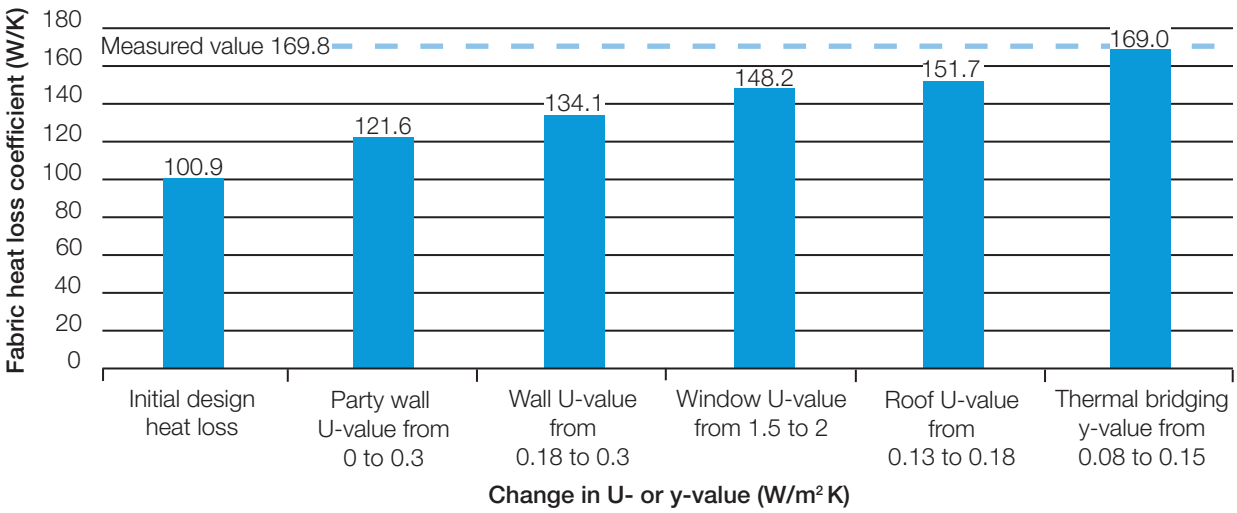
- **Thermal bridging** Additional heat loss at junctions and around windows was assumed in design to be the equivalent of the default value in SAP for dwelling designs that makes use of a standard catalogue of the Government's 'accredited details' (CLG, 2006c). However, observations of the design and the complexity of the junctions suggested that the thermal bridging values used in designs were not appropriate. In addition, it was clear from inspection of design drawings and from observations of construction that there was a high likelihood of other thermal bypasses at certain junctions, in addition to the party wall bypass. The estimated impact of thermal bridging and additional bypassing was an increase in heat loss equivalent to about 0.15 W/m²K across the whole of the thermal envelope.

It is clear from the measurements and observations that the realised U-values of the various construction elements and junctions, as-built, do not match the estimated values used in design. The results of the forensic examination provided a reasonable evidence base from which to postulate alternative values for dwelling fabric performance that would match what was measured in the coheating test.

Figure 12 sets out a revised heat loss calculation for the end-terrace dwelling, showing the cumulative impact of each change from the initial design heat loss to a recalculated whole dwelling loss. This is compared with the measured value. All values are derived from estimates based on the forensic examination and resulted in U-values of 0.3 W/m²K for the walls, 0.18 W/m²K for the roof, 2.0 W/m²K for the windows, 0.15 W/m²K for the thermal bridging y-value, and an additional heat loss for the party wall characterised by an effective U-value of 0.3 W/m²K. No adjustment was made to the U-value of the floor.

The calculated fabric heat loss coefficient with all adjustments was 169.0 W/K. This value is very close to the measured fabric heat loss coefficient of 169.8 W/K obtained from the coheating test. Although one needs to be cautious about finding such a fit when one knows the expected value in advance, it is clear that the observed value from the coheating test can be explained by the observed thermal performance characteristics of the building elements and junctions. The empirical calculations suggest that the largest contributor to the increase in fabric heat loss for the end terrace was the party wall thermal bypass, which accounted for 20.7 W/K (31 per cent) of the total predicted difference. The increase in wall and roof U-values adds 16 W/K (23 per cent), windows 14.1 W/K (21 per cent) and the thermal bridging y-value increase some 17.3 W/K (25 per cent).[21]

Figure 12: Closing the loop between initial design fabric heat loss and measured heat loss



Air tightness

All six dwellings were pressure tested at completion to measure their air tightness. The value for the end terrace (the coheating tested dwelling) is that obtained at the end of the coheating test before it was handed back to the contractor.[22] The air permeability results ranged from 6.2 $m^3/(h.m^2)$@50Pa for the duplex apartment (House E) to 8.6 $m^3/(h.m^2)$ for the ground floor flat (House C). The mean completion air permeability for all six dwellings was 7.01 $m^3/(h.m^2)$. In all cases the air permeability was within the upper limit (10 $m^3/(h.m^2)$) set by the Building Regulations but well above the value (3 $m^3/(h.m^2)$) contained in the original outline specification in April 2006.

The air tightness results are fairly typical of current UK mass housing. Figure 13 compares the air tightness achieved at Elm Tree Mews with air tightness distributions from a sample of dwellings constructed to the 2002 regulations (Grigg, 2004), 2006 regulations (NHBC, 2008) and from the Stamford Brook low energy field trial (Wingfield, *et al.*, 2008).[23] It is clear that, for a low energy scheme, the air tightness performance at Elm Tree Mews was well above the range one might have expected, even for a moderately efficient scheme such as Stamford Brook, which had a target specification of 5 $m^3/(h.m^2)$. Also, it is anticipated that levels of air tightness are likely to deteriorate as the dwellings mature.

As indicated above, the air tightness target was not made explicit in the detailed design documentation, despite the initial aspirations of achieving a relatively low figure of 3 $m^3/(h.m^2)$. The lack of an explicit target and detailed design for air tightness has resulted in values that are well above those that would be expected for a low energy housing scheme. Had the target of 3 $m^3/(h.m^2)$ been maintained, the heat loss from air leakage would have been some 50 per cent lower (13 W/K) than the measured value and some 70 per cent (31 W/K) lower than the nominal value used in the Building Regulations SAP submission. However, it is likely that to reap the benefit of low air permeability and to ensure adequate indoor air quality, a change to the ventilation system would have been required, incorporating high performance heat recovery ventilation.

Some of the difficulties encountered were directly related to the complexity of the geometry and the difficulties of maintaining a continuous air barrier at junctions. The complexity of the roof design and the

Figure 13: Elm Tree Mews air tightness compared with post-2002 and 2006 regulatory regimes and the Stamford Brook Low Energy Masonry Scheme

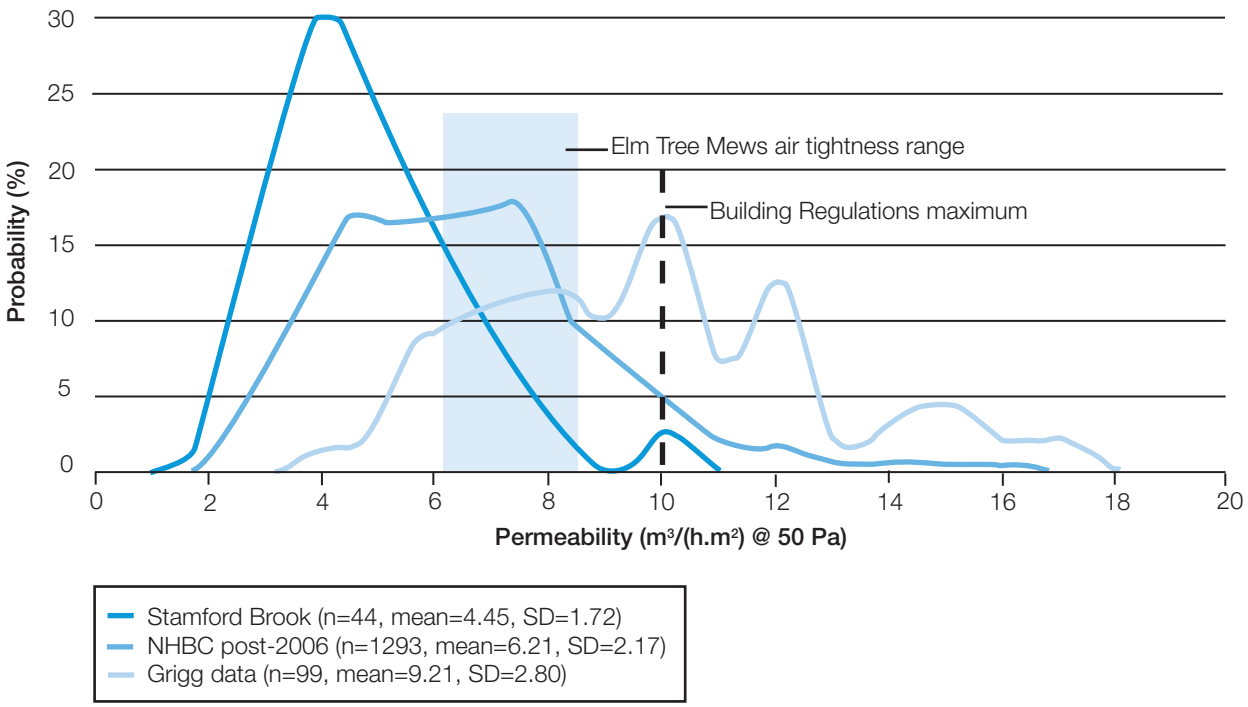
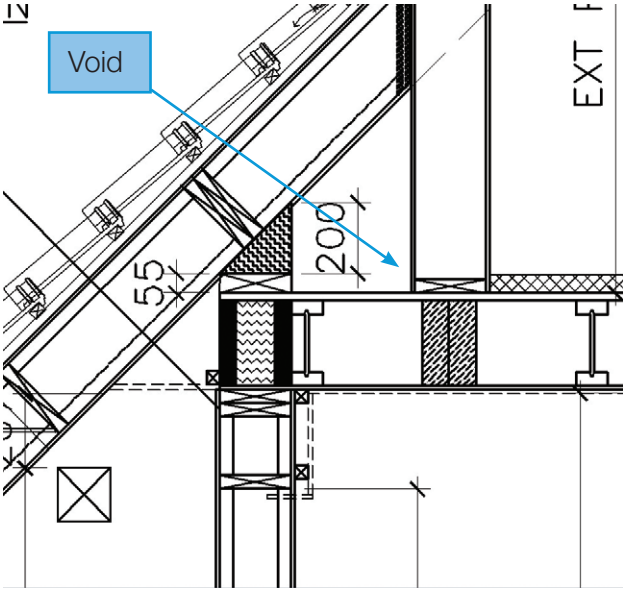


Figure 14: First floor and dormer window junction



Junction of roof and dormer window at first floor ceiling

Junction under construction

detailing of the dormer windows resulted in the formation of small voids at junctions. The intermediate floor between the first and second floors is shown in Figure 14. This is a difficult junction to design in terms of air tightness since maintaining continuity of the air barrier at this point (shown by blue lines) would require some careful consideration of the design of the air barrier, selection of appropriate materials and careful sequencing. Perhaps the simplest solution in this case would have been to design the junction with a membrane that wraps the end of the intermediate floor so that it could have been linked with the internal air barriers, together with an appropriate series of construction steps planned to ensure correct installation of the membrane. The issue here is not that the aesthetic requirements of the scheme should be unduly sacrificed but, rather, that the impact on the detail design of air tightness needs to be understood and design resources applied accordingly.

The issue of air tightness design has important implications not only for thermal performance but also for the design of the ventilation system. It would seem, from both design documentation and construction observations, that air tightness did not feature as an important design issue. However, even with the lack of any explicit design for air tightness there would always be a risk that the scheme would have been air tight purely by chance. If this had taken place, it is likely that the designed ventilation system, which consisted of intermittent extractor fans in kitchens and bathrooms and manually operated trickle vents, would not have provided adequate indoor air quality. In the event, the results obtained were to be welcomed given the ventilation system design.

Initial performance of heating and hot water services

The initial performance of heating and hot water services was measured through manual meter readings undertaken prior to occupation. The objective at pre-occupation stage was to gain an understanding of the commissioning process, in particular the settings of the heat pump and solar hot water systems and of their control.

Initial heat pump performance

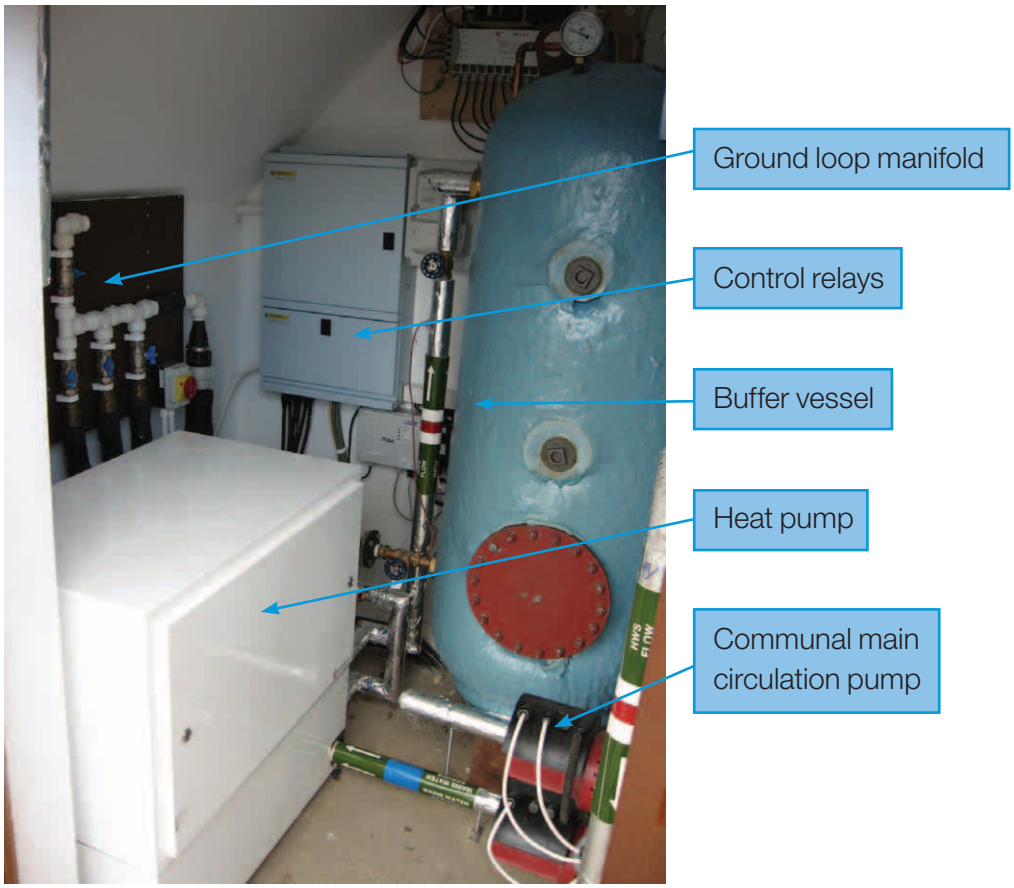
Figure 15 shows the layout of the plant room with the heat pump, buffer tank, circulation pump and controls. Following commissioning in March 2008 the heat pump was left operating while the finishes and decoration of the dwellings were being completed. From 2 May to 26 June 2008, a number of manual readings were taken, which provided data for six discrete periods ranging from twelve days to six days in length. Although a full discussion of the heat pump operation will follow the discussion of in-use monitoring in Chapter 4, the post-commissioning evaluation identified the following performance issues:

- Hot water cylinder thermostat settings (60°C – normal for a conventional boiler) were not adjusted to account for lower temperature output of the heat pump. A setting of 45°C would have been more appropriate. This resulted in the main circulation pump operating at maximum speed and power (435 W) for 100 per cent of the time. Adjusting the thermostats and correcting a wiring fault in one of the dwellings improved the system considerably. Subsequent circulation pump energy was reduced almost tenfold during the other evaluation periods.

- The heat pump design included an internal circulation pump that was designed to run continuously, even when there was no call for heat. The result in low-load conditions was to reduce the heat pump CoP to values that ranged from 1.8 to an extreme 0.18 in one six-day period. This same issue had been picked up in a previous study of the performance of a heat pump in a single dwelling (BRECSU, 2000), where an 87 W distribution pump was found to run continuously, even when the system was not calling for heat. Later in the monitoring period the control problem was resolved along with changing the internal pump altogether since it was oversized for the buffer tank system.

The issues identified post-installation and commissioning point to a number of questions about both system design and system commissioning. From a design point of view, the design of the system as a

Figure 15: Plant room layout showing the main components of the communal heat pump



whole, including the relationship between the different components and their control, did not appear to be sufficiently robust. Similarly, the commissioning process focused on individual components but did not consider the interactions between the different elements. The problems could have been a result of a lack of system commissioning planning, poor communication or insufficiently detailed system specification. Given the number of consultants and subcontractors involved, a combination of all three factors is likely. The observations would suggest that the design and commissioning procedures for relatively complex heating systems such as that at Elm Tree Mews will require more detailed work and planning than for a dwelling heated by a gas boiler.

Initial performance of the solar water heating system

The main components of the solar hot water system (solar panel, solar pump and controller) were installed by the solar heating subcontractor. The other key components of the domestic hot water system such as the cylinder, heat pump connection to cylinder, plumbing connections, timers, valves, electrical connections and the insulated pipe work between the solar panel and cylinder were installed by the main M&E subcontractor. The solar systems were filled with Tyfocor GLS heat exchange fluid at the end of April 2008, when all other parts of the hot water system had been completed.

The commissioning certificates for the solar hot water systems indicated that the systems were working satisfactorily in all six dwellings. However, concerns were raised about the performance of the solar system soon after commissioning. Readings from the solar heat meters at the start of May showed significant differences in the recorded solar inputs to each dwelling. In particular, the solar heat meter readings in dwellings A and D were significantly below the other four dwellings. Observations made by the research team in House D in the first week of May showed that the solar heat pump was short cycling and that the solar system pressures were only around 1 bar (compared to around 2.5 bar for the system in the unoccupied end terrace).

Further investigation of a number of problems with the solar systems took place both during the pre-occupation phase and during the first few months' occupation. Indeed it was not until the end of July 2009, some twelve months after occupation, that the systems could be said to be working reasonably well in all dwellings. The performance issues that were identified are set out below.

- **Flow restriction** The low levels of solar input to dwellings were eventually traced to flow restrictions caused by kinked pipe work buried in the service void at the party wall at the second floor junction (Figure 16). In two of the dwellings the restriction was sufficient to require remedial works and, in a further dwelling, reduced flow was noted but it was not sufficient to warrant the disturbance in rectifying the fault.

- **Leaks** Leaks occurred in a number of systems, one of which was the result of a nail from skirting fixing. This is a common problem with pipe layouts that are largely unplanned and not well coordinated.

- **Overheating** In one dwelling the solar system overheated because the dwelling was unoccupied for a long period during sunny weather and there was no hot water being drawn from the system. This resulted in the pressure release valve venting solar fluid onto the roof and the need to refill the system. Design features could have been built into the system that would have accommodated such a situation, which is arguably not that unusual.

- **Flow direction** In two dwellings the flow and return pipes to the panel were plumbed the opposite way around. Although this did not prevent the fluid from flowing, it reduced the effectiveness of the systems since the design of the panels and their control was geared to the specified flow direction.

- **Control sensor wiring** The panel temperature sensors for two dwellings were interchanged due to confusion over the control wiring. This meant that the panel serving one of the dwellings was being controlled by the temperature sensor for an adjacent panel serving another dwelling with a different demand profile.

- **Circulation pump mode** In one instance the solar circulation pump was left in manual mode, which resulted in it running continuously. The manual mode is used during commissioning, but in this case the system had not been switched back to automatic control when commissioning was complete. This oversight was only detected from monitoring data. The impact on the system was that the pump used energy unnecessarily but also took heat out of the hot water cylinder during the night or cold cloudy periods.

- **Freeze protection** In two dwellings the systems were set to provide a freeze protection cycle as would normally be used with water-only systems in climates where freezing risk is low. Since the systems at Elm Tree Mews were filled with an antifreeze solution, not only was this setting unnecessary but the protection cycle would operate the pump when the temperature at the panel approached freezing so as to heat the panel from the stored hot water.

Overall, there were seven specific performance issues that affected the dwellings with solar hot water systems. There was only one dwelling out of the six that experienced no installation or operational problems. Although each incident had its own specific causes, the experience suggested that there were problems of a systemic nature to do with the process of design, commissioning and installation. The choice of a system that could not cope with an extended period of no hot water consumption coupled with commissioning procedures that were not able to detect faults in the installation and the lack of defined services routes, which would have reduced the risk of inadvertent damage, suggest that processes were not robust and were likely to lead to the sort of problems identified. These and similar issues are taken up in the discussion of systems and processes in Chapter 5.

Figure 16: Flow restriction in solar system due to kinked malleable copper pipe

Kinked solar pipe work at wall/floor junction

Pre-insulated malleable copper pipe used for the solar hot water systyem

Principal findings on post-construction performance

The findings of the post-construction phase assessment have revealed a level of fabric performance that is well below that intended at the design stage. However, the forensic examination and analysis provide some very useful positive lessons, which can be used to provide sound design advice. These can be summarised as follows:

- An explicit investigation of the wall and roof panel construction at design stage would have highlighted the problem of a high timber fraction and a recalculation of the wall U-value would have highlighted the need to address the thermal implications of the structural design. Indeed, it is likely that, had the nominal U-value been challenged, this would have precipitated a change in the detailed design of the wall construction involving an external insulation layer that was not so prone to the bridging effects of structural elements.

- The calculation of thermal bridges would have revealed many of the difficulties involved and informed the detail design of many of the junctions. Although this would have required more staff resources it would have added considerable value to the thermal design process.

- The design of the party wall and other areas prone to thermal bypassing has now been exposed and solutions are beginning to emerge (see, for example, Wingfield, *et al.*, 2009; Wingfield, *et al.*, 2010). For instance, it is likely that filling the party wall with mineral fibre insulation and improving the edge sealing (as now recommended in regulatory guidance, CLG, 2010) would reduce the party wall heat loss to zero. Also, ensuring that the air barrier and the insulation layer are in constant contact will avoid other bypasses.

- Adopting a different approach to product substitution in which performance characteristics are much more explicit and substitution performance checked much more rigorously would have reduced the risk of underperformance of the substituted windows during construction.

The investigation of initial performance of heating and hot water services identified shortcomings with the design, installation and commissioning of the heating and hot water services. The design of services tended to underestimate the interactions between components and the complexity of the control requirements. There is a need for much greater emphasis on whole system design, particularly when the systems are relatively new, as in the case of Elm Tree Mews. The construction problems associated, most notably with the solar water systems, demonstrate a need for much closer control of installation backed up by design. Finally, commissioning processes were not robust enough to detect many instances of underperformance.

Many of the issues raised have important implications not only for the detailed design of the technology but also for the processes by which design and construction decisions are made, and the way the processes are managed. These implications are addressed in Chapter 5, following an exploration in Chapter 4 of post-occupation performance.

4 Post-occupation performance

One of the key concerns of this study has been with the performance of the dwellings following occupation by the residents. Together, the dwelling and its occupants form an integrated system in which people live their lives and, in the process, use energy and emit carbon. The relationship between a dwelling and its occupants is highly complex and varies over time. Indeed, it has been suggested that home is much more than simply bricks and mortar. It is imbued with meanings of attachment and rootedness, where people feel a sense of control over space and can withdraw from the rigours of the outside world (Seamon, 1979; Cresswell, 2004). Arguably, how people use a property relates as much to their own set of personal circumstances as to the appliances and systems that are available within it. Producing successful sustainable housing is therefore as much about understanding this relationship and supporting household needs as improving the fabric performance. This chapter considers this relationship and its energy consequences through the detailed monitoring of the dwellings, informal day-to-day contact between researchers and residents during the monitoring period and the formal post-occupancy interviews. It is organised in a number of sections that deal with the different elements of in-house energy consumption and internal property conditions, such as temperature and ventilation, and concludes by focusing on the key themes that arise from this relationship between dwelling and household needs.

Three of the occupied dwellings (Houses A, B and C, see Table 4) were monitored for a full year or more, from September 2008 to September 2009, with the remaining two occupied dwellings (Houses D and E) being monitored for eight months, from January to September 2009, which covered only part of the heating season. Occupancy levels of the five occupied dwellings at Elm Tree Mews were ascertained from the initial discussions with the residents and from the final interviews, and are shown in Table 4. It should be noted that House C was occupied intermittently, due to the nature of the tenant's employment, typically for only one or two days per week. This would significantly affect energy consumption and hot water use for this dwelling compared to the expected use. The table also shows the range of household types and the working status of residents, which will affect their needs, how they interact with the dwellings and use household appliances.

Table 4: Dwellings and households at Elm Tree Mews

Dwelling code	House type	Occupancy level	Household type	Employed?	Number of children under 16	Member of household with a disability?
A	Mid-terrace	4 + 1 dog	Family	No	2	Yes
B	Mid-terrace	5	Family	No	3	No
C	Flat	1 (Intermittent occupation)	Single	Full time	n/a	No
D	Mid-terrace	3 + 1 cat	Single parent family	Part time	2	No
E	Flat	1	Single	Full time	n/a	No

The performance and efficiency of the communal heat pump at Elm Tree Mews were monitored from July 2008 until the end of September 2009. A heat meter and kWh meters were installed on the heat pump and system components, and a series of temperature sensors were located on the flow and return pipe work to and from the heat pump, buffer tank, communal main and ground loop. Table 3 (Chapter 2) sets out the principal monitoring approach and the technical report (Wingfield, *et al.*, 2010) provides further detail. In undertaking the analysis of consumption it is important to note that the heat pump system was out of action for a few weeks in February 2009 and this event is noticeable in the data sets presented. As a general rule, the consumption data for February, although presented in graphs, is discounted in the discussion. However, it was a source of obvious concern for residents. In some dwellings, living room temperatures (daily average) fell to as little as 12 to 15°C, which is a particularly low average in what is usually the most well-heated room. As one female resident observed:

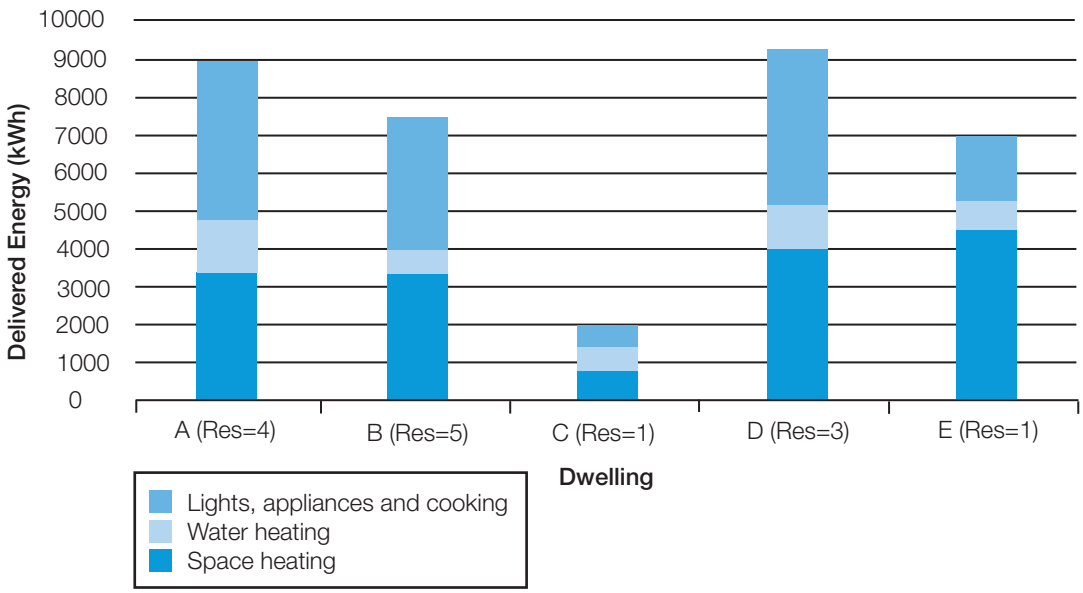
> *They came round on the Friday and gave us electric heaters and then it snowed. Then the part [for the heat pump] was coming from Cornwall, and the truck couldn't get from Cornwall to York, so it took about two weeks. So we didn't have any hot water. We had to use the immersion for the hot water and we didn't have any heating.*

Due to technical problems with the heating and hot water systems over the first six months of occupation, initial interviews were not conducted to avoid any negative bias in the interview responses as a result of the technical issues, and also to minimise further disturbance to the householders. The qualitative exploration of the ways in which residents used the dwellings therefore centred on the final interviews, which took place at the end of the in-use monitoring period. At the same time as the interviews were conducted, the temperature and energy sensors were removed from the dwellings. The semi-structured interviews (lasting between 30 minutes and an hour) were used to gauge residents' responses to the properties and how they made use of them. Residents were also provided with feedback on the energy performance and internal conditions of their homes.

Energy usage

In this section we provide an overview of energy consumption over the twelve-month monitoring period and compare this with monitoring data from the Stamford Brook field trial (Wingfield, *et al.*, 2008). Energy

Figure 17: Annual delivered energy consumption



consumption is compared also with SAP model predictions for each household modified to account for the additional information provided by the monitoring data. In this way we are able to 'close the design loop', comparing realistic modelling with actual consumption. Although important, annual data does not provide a great deal of understanding about the interactions between the dwellings and residents. In order to unpick some of the issues we summarise monthly patterns of consumption and the implications for the resident experience.

Annual energy consumption

Annual delivered energy consumption for the five dwellings monitored is set out in Figure 17.[24] The three mid-terrace dwellings displayed similar space heat consumption and Houses A and D were quite similar overall. House D used about half as much energy for water heating as the other two mid-terrace households despite having the highest occupancy. This would appear to be the result of lower water usage, which is discussed below. However, it must also be considered that in all cases there would have been energy from the solar systems, which the analysis did not include because of the difficulties with the systems. Interestingly, the single person household in House E (duplex flat) had the highest space heating consumption but low water and household appliance consumption. As discussed below, the higher space heating energy is likely to be a function of the complex interplay between heat gains from occupants and the appliances they use, particularly in relatively well-insulated dwellings, and the demand for delivered heat.

When normalised for floor area (see Figure 18), House E, which is about two thirds the size of the terraced houses, is the highest energy consumer per square metre with the largest proportion of space heating, at about 65 per cent of the total. Space heating in House E (60 kWh/m^2) is about twice as high as that in the mid-terrace dwellings (30–35 kWh/m^2). In contrast to the position in most of the existing housing stock, the energy consumption for lights, appliances and cooking is on a par with space and water heating in the terraced dwellings. Such a position is to be expected as levels of insulation increase and drive down space heat demand. The intermittent occupation of House C is reflected in the significantly low consumption of all energy.

Figure 18: Annual delivered energy normalised by floor area

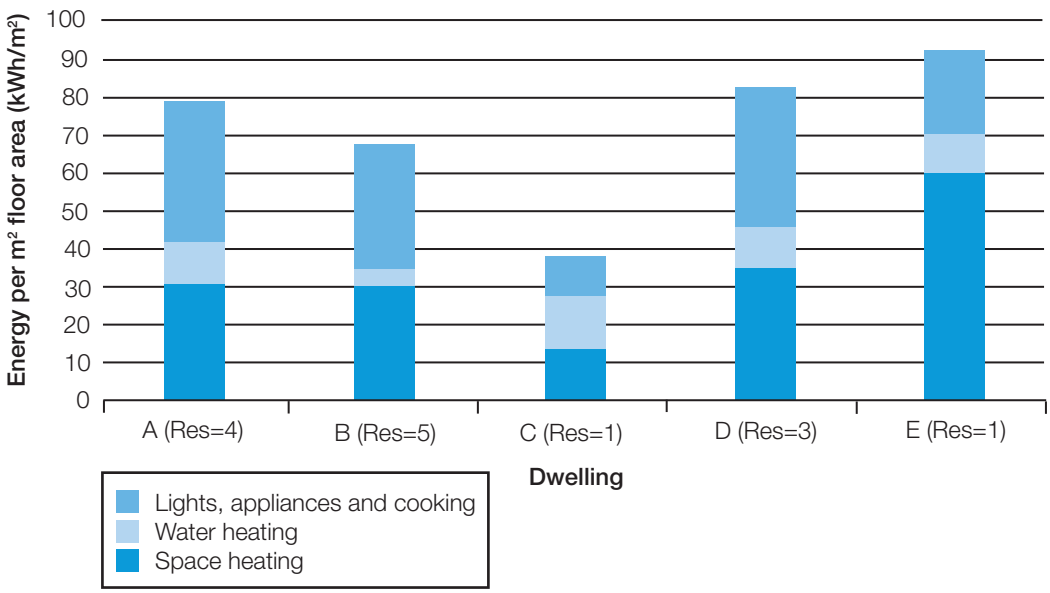
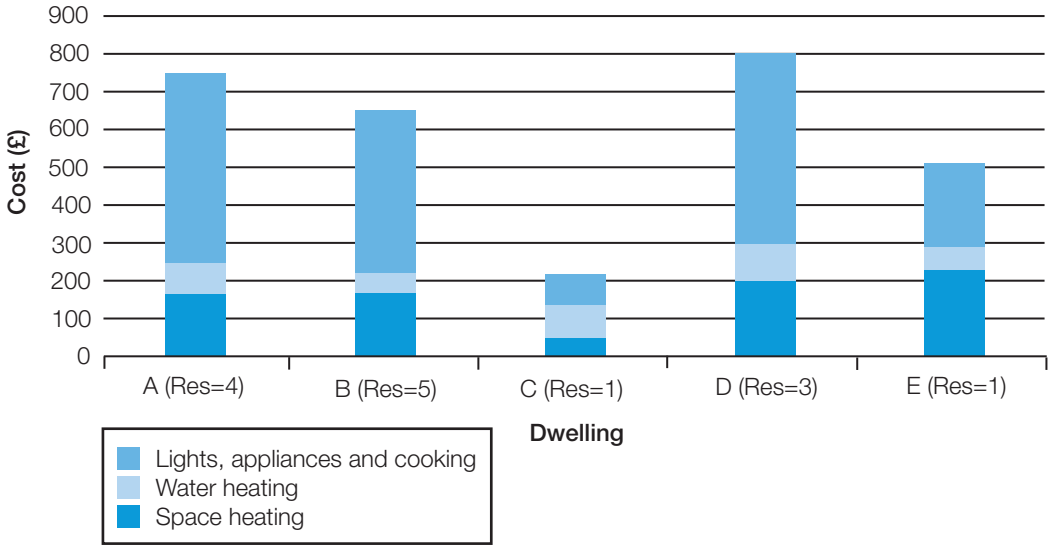


Figure 19: Annual delivered energy cost (£)



Annual energy cost

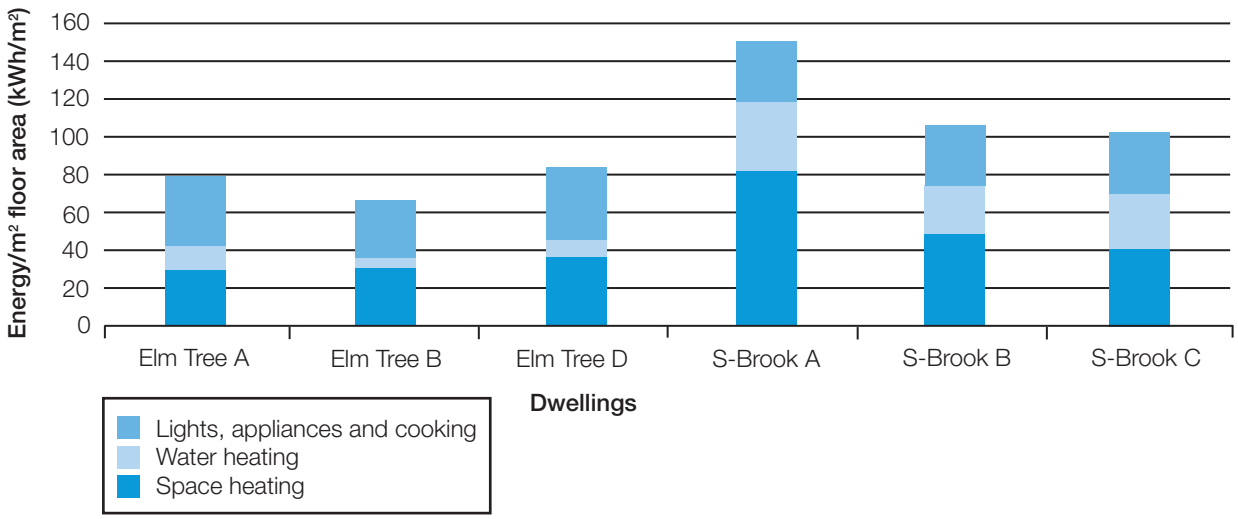
In a scheme such as Elm Tree Mews, energy cost is of particular importance to the social landlord as well as the residents. The cost is made up of the tariff for heat provided from the communal heat pump and that of the electricity supplied for each dwelling. For the purposes of this analysis, the actual tariff for delivered heat and a mid-range electricity tariff for the Yorkshire region have been applied. Figure 19 shows the costs for each dwelling. In reviewing these costs it is important to note the structure of the heat tariff. This is the result of a complicated calculation to derive the cost of heat and is based on the electricity tariff paid by the landlord, the performance of the heat pump (this had to be estimated in advance of the monitoring results and is a crucial factor), the management charge from the metering company and the maintenance costs of the communal system. Given the underperformance of the heat pump, it is possible that the tariff is an underestimate of the true cost of providing heat. This is a point we return to in Chapter 6.

The most striking pattern is the relatively high cost for electrical appliances and cooking in the mid-terrace houses when compared with the costs of heat for space and water heating. In the terraced houses space and water heating costs are between £225 and £300 per annum (£4.30 to £5.77 per week, £18.75 to £25.00 per month) compared with between £430 to £500 per annum (£8.27 to £9.61 per week) for lights, appliances and cooking. To some extent this is a function of the use of the heat pump, which will reduce the cost of heat even at a less than anticipated CoP (2.15 as opposed to 3.2). Similarly, the availability of 'free' solar heat will have had some impact on the amount of delivered energy required for hot water despite the problems with the solar systems. The pattern in House E (duplex flat in single occupancy) shows that costs are more evenly split and the intermittent occupancy in House C has clearly impacted on the pattern of energy usage and cost.

Energy and carbon comparisons

Making comparisons with data from other schemes is fraught with difficulty since it is impossible to achieve a like-for-like comparison, especially when the numbers monitored are small. Comparisons with national data sets are even more problematic. However, in order to provide a general point of comparison, the results at Elm Tree Mews were compared with those from the Stamford Brook project. The nominal energy standard at Elm Tree Mews was around 40 per cent in advance of the 2006 regulations and Stamford Brook 10 per cent in advance of 2006. Figure 20 compares the energy consumption (normalised for floor

Figure 20: Energy comparison – Elm Tree Mews and Stamford Brook (Wingfield, *et al.*, 2008)



area) for the mid-terrace houses at Elm Tree Mews with the terraced houses at Stamford Brook.[25] In broad terms, the Elm Tree Mews dwellings would appear to use less energy for space and water heating than the Stamford Brook dwellings. However, the difference is not particularly large, given the difference between the two energy standards. The exception is the Stamford Brook dwelling A, which was the highest user among those monitored at Stamford Brook as a result of specific usage factors relating to high levels of window opening, higher internal temperatures and cooking. The difference is also heavily influenced by occupation and a raft of usage factors that confound the comparison. The only factor that appears to stand out is the difference in hot water energy. The lower water heating energy at Elm Tree Mews will have been influenced by the access to solar energy, differences in water consumption (particularly House B) and the generally lower hot water temperature at Elm Tree Mews.

As indicated in Figure 21, if carbon emission rates are compared using SAP 2009 carbon emission coefficients (due to come into force in October 2010), the difference between the two data sets becomes

Figure 21: Carbon emission comparison – Elm Tree Mews and Stamford Brook (Wingfield, *et al.*, 2008)

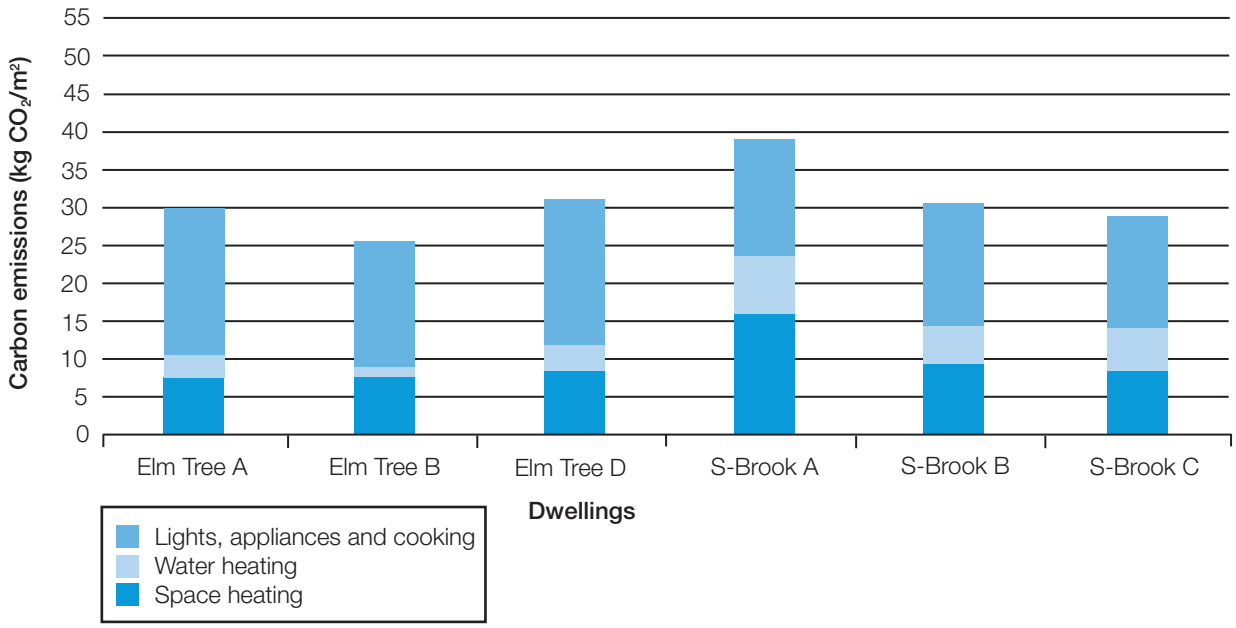


Table 5: Modelled and measured annual space heating: House A and House B

Description of measured and modelled parameters (12 months – 24/09/2008 to 23/09/2009)	House A	House B
Measured annual heat input – heat main only (kWh)	3,463	3,409
Modelled annual heat requirement – standard assumptions (kWh)	3,439	3,505
Measured annual heat input – heat main plus heat from electric heaters in February when heat pump out of action and extra gains from appliances	4,509	4,282
Modelled heating requirement – adjusted for actual conditions exc. fabric (kWh)	1,776	1,878
Modelled heating requirement – adjusted for actual conditions inc. fabric (kWh)	4,308	5,128

even less marked. This reflects the differences in the carbon intensity of the different fuels. The SAP 2009 value for the carbon intensity of electricity (0.517 $kgCO_2$/kWh), the fuel used for space and water heating at Elm Tree Mews, is just over two and a half times that of gas (0.198 $kgCO_2$/kWh), the fuel used at Stamford Brook.

Closing the loop – predicted versus measured space heating

Perhaps a much more relevant comparison is to assess actual performance of the systems compared with design expectations. The measured annual space heat input data for Houses A and B (the dwellings with the most complete twelve-month data set) was analysed over the same period (24 September 2008 to 23 September 2009) and was compared with the heat input requirement that was predicted using the Leeds Met parametric domestic energy calculator (a parametric implementation of SAP 2005) (Lowe, *et al*., 2008).[26]

Table 5 compares the measured input with the modelled heating input under different assumptions. At first glance it would appear that, for both houses, there is very close agreement between the prediction at design stage (line 2 in Table 5) and that measured from the heat main (line 1). However, the measured heat input needs to be adjusted to account for fan heater electricity used during February when the heat pump was out of action and for the extra heat gain from electrical appliances (as measured during monitoring) over and above that assumed in the SAP model (line 3). This increases the heat input to 4,509 and 4,282 for Houses A and B, respectively. In addition, standard use, external temperature and other assumptions made by SAP do not accord with the actual usage or external conditions that were observed. If the heating energy requirement is calculated using actual usage conditions (occupancy, ventilation rates, internal and external temperatures) the heat requirement in both dwellings falls considerably to 1,776 kWh/annum for House A and 1,878 kWh/annum for House B (line 4 in Table 5).[27] Under actual conditions over the monitoring period House A is using some 2,733 kWh/annum (+154 per cent) more for heating than predicted and in House B the corresponding value is 2,404 kWh/annum (+128 per cent). These figures assume that the performance of the fabric is as-designed. However, if one takes into account the measured fabric performance (see Chapter 3), then the predicted values are much closer to those measured (line 5 and line 3). In the case of House A the difference between the as-built modelled and measured is -201 kWh and in the case of House B is +846 kWh.

This discussion illustrates the difficulty of using modelling and in-use energy data alone in evaluating performance of low energy housing schemes. In the case of Elm Tree Mews, if one had undertaken monitoring of delivered heat main energy only, and then compared this with design model predictions using standard assumptions, the erroneous conclusion could have been drawn that the building was performing as expected. However, the fabric performance and other measurements reveal that this is not the case.

Clearly, considerable care is required when using energy performance models with which to compare actual energy consumption since the models are critically dependent on the assumptions made about use-characteristics and the performance of fabric and systems. This is especially true for highly insulated low energy housing where factors such as internal gains and solar gains can have a much larger relative impact on heating energy demand than in less well-insulated dwellings.

Carbon emissions from space and water heating

The monitored energy data for space and water heating showed that the total electricity used by all six dwellings combined over the period from September 2008 to September 2009 was 15,100 kWh (12,600 kWh for the heat pump and 2,500 kWh for the immersion heaters).[28] If the current carbon emission coefficient for grid electricity is applied (0.422 kgCO_2/kWh, SAP 2005; see BRE, 2005), the total carbon emissions for all six dwellings would be estimated at 6.37 tonnes CO_2/annum. However, the applicable carbon coefficients have been reviewed recently (Pout, 2009a; Pout, 2009b) and are set to change in October 2010 when revised Building Regulations come into force (CLG, 2010), which incorporate the new version of SAP (SAP 2009; BRE, 2010). If the new coefficient is applied (0.517 kgCO_2/kWh) estimated emissions would be higher at 7.81 tonnes CO_2/annum.[29]

Putting this data into context, the fabric performance tests and heat pump CoP measurements (see below) indicate that energy consumption and carbon emissions would have been much lower if both the building fabric and heating and hot water systems had performed as designed. Based on the investigation of actual fabric and services performance it is estimated that, had fabric and heat pump performed as expected, electricity consumption would have been of the order of 6,300 kWh, which is equivalent to 2.66 tonnes CO_2/annum, assuming SAP 2005 coefficients and 3.26 tonnes CO_2/annum if SAP 2009 factors were used. Thus the extra CO_2 emitted as a result of fabric and services underperformance was in the region of 3.7 tonnes CO_2/annum based on SAP 2005 and 4.55 based on SAP 2009, an increase of some 140 per cent.

The design decision to use a heat pump rather than gas-condensing boilers was dependent on the assumptions made about the efficiency (CoP) of the heat pump and the relative carbon coefficients for mains gas and grid electricity. In order to understand the dynamics and sensitivities involved, it is useful to assess the impact on the design decision of both the underperformance of the dwellings and the change in carbon emission coefficients. For the purposes of this analysis, the data presented in Table 6 has been extrapolated from the measured data and adjusted to account for the underperformance of the fabric. This means that the energy consumption and carbon emissions presented in Table 6 assume that the fabric behaved as designed and therefore are less than the measured data.

Table 6 sets out the impact of the changes. It is clear that, using SAP 2005 carbon coefficients, had the heat pump delivered the performance anticipated, the decision in 2006 to switch from gas boilers to a communal heat pump was well founded with projected savings of 0.68 tonnes CO_2/annum. However, the actual system performance (CoP = 2.15) makes the decision much more marginal. A gas boiler operating at a realistic 85 per cent efficiency would have produced less carbon, albeit with only a small saving (0.1 tonnes CO_2/annum).[30] Under SAP 2009 carbon coefficients, the original decision to use a heat pump would have remained viable if the heat pump system had met design expectations but the saving (0.15 tonnes CO_2/annum) would have been much reduced. However, the impact of a lower actual CoP and increased emission factors mean that the case for a gas system is stronger with a saving of 0.8 tonnes CO_2/annum. Interestingly, if the analysis is repeated, taking into account actual fabric performance, a heat pump system operating at a CoP of 3.2 would result in less carbon per annum under both 2005 and 2009 emission rate scenarios and even at the actual CoP (2.15) would still be marginally beneficial under the 2005 coefficient scenario. However, at the 2009 emission coefficients the heat pump underperformance (CoP = 2.15) results in some 0.9 tonnes CO_2/annum more than a gas boiler system (6.78 tonnes for the gas system compared with 7.69 tonnes for the heat pump system).

This example clearly demonstrates the difficulties of design decision-making in the shifting sands of national carbon emission factors, the complex interplay between efficiencies and fabric performance and uncertainties about as-constructed or as-installed performance. From a national policy perspective it is important that designers are able to understand the likely trajectory of carbon emission coefficients, particularly of electricity, and to be able to test the sensitivities involved when making design decisions. It is therefore necessary for the Government to provide a stable platform rooted in robust long-term energy and carbon policy. This is a topic to which we return in Chapter 6. Although there is much that can be done by government to provide a stable environment for design decision, there is a lot that needs to be done by the industry at large in reducing the uncertainties involved in the performance of fabric and services.

Patterns of energy consumption

Electricity consumption and space heating

The detailed data on energy use is discussed in the technical report and summarised here. In all dwellings space heating was provided by heat delivered from the ground source heat pump via the heat main. Hot water was provided by a complex mix of heat from the heat main, solar heat from the solar panels and heat from the electric immersion heater. The remaining energy consumption consisted of electricity used for lights and domestic appliances. Figure 22 shows the daily mean electricity consumption for each month and Figure 23 the daily mean space heating energy per month. More detailed data is presented in the technical report, from which the following energy consumption characteristics of electricity consumption and space heating can be identified.

- As would be expected, electricity consumption (Figure 22) displayed a clear split between the single occupancy households (the two flats, Houses C and E) consuming in the region of 2 to 5 kWh/day and the mid-terrace dwellings occupied by between three and five residents consuming around 10 to 12 kWh/day. The levels of daily consumption appeared to be reasonably consistent across the year with the exception of House C (single floor flat), which was occupied intermittently.

Table 6: Comparison of gas boiler versus heat pump, SAP 2005 and 2009 carbon coefficients (data extrapolated from measured data and adjusted to account for fabric underperformance)

	Individual gas condensing boilers	Communal heat pump (expected CoP)	Communal heat pump (actual CoP)
Main heating system efficiency %	85%	320%	215%
Immersion heating efficiency %	n/a	100	100
Delivered heat from main heating system (kWh)	14,650	12,150	12,150
Delivered immersion heating input (kWh)	n/a	2,500	2,500
Total delivered fuel (gas/electrical energy – kWh)	17,235	6,297	8,151
Carbon coefficient SAP 2005 (kgCO_2/kWh)	0.194	0.422	0.422
Heating carbon emissions (tonnes CO_2/annum)	3.34	2.66	3.44
Carbon coefficient SAP 2009 (kgCO_2/kWh)	0.198	0.517	0.517
Heating carbon emissions (tonnes CO_2/annum)	3.41	3.26	4.21

- When compared with regional and national averages, annual electricity consumption for each of the terraced dwellings was in the upper 50 per cent of consumption. Although in the upper grouping they were broadly typical of many UK households.

- Delivered space heat followed a typical pattern in all dwellings (Figure 23) with the highest consumptions in the winter (which was only marginally below the 20-year average) and the least in the summer. However, unlike electricity consumption, the effect of the number of household members was less marked. Of course, the intermittently occupied flat had relatively low consumption, reflecting the special patterns in this case. Yet the heat demand for the other single resident household (House E) was, if anything, slightly higher than that of the terraced houses with three to five residents per household. In fact the higher heat demand in House E would be more marked if normalised for its smaller floor area.[31]

A comparison of the energy consumption data for electricity consumption (Figure 22) and delivered space heat (Figure 23) for House E provides an important illustration of the complex interactions between these two, seemingly unconnected, aspects of consumption. The higher heat demand can be explained, in part, by the fact that, House E is occupied by a single resident, using a small amount of electrical energy. This means that the incidental heat gain from people and appliances is much less than in the more intensely occupied mid-terrace dwellings. The net effect is an increased heat requirement to make up for the lower incidental gains. Although this may appear to be an obscure technical point, the interplay between gains and heating is of increasing importance in well-insulated dwellings and needs to be fully understood when interpreting monitoring data of the kind collected at Elm Tree Mews. What makes this a particularly interesting example is the fact that the resident in House E is extremely conscious of her energy and heating demands and deliberately attempts to minimise any excess use of energy:

> *I am very cautious … All of the appliances are switched off at the wall, all the time, apart from the fridge and the freezer and the alarm clock. So the TV and DVD and all the gadgets are switched off at the wall all the time.*

However, she is less concerned about using the heating because, as she said, 'it made a huge difference to know that I could have the heating on and not worry about the effect it was having on my carbon footprint'.

Figure 22: Plot of daily mean electricity use by month

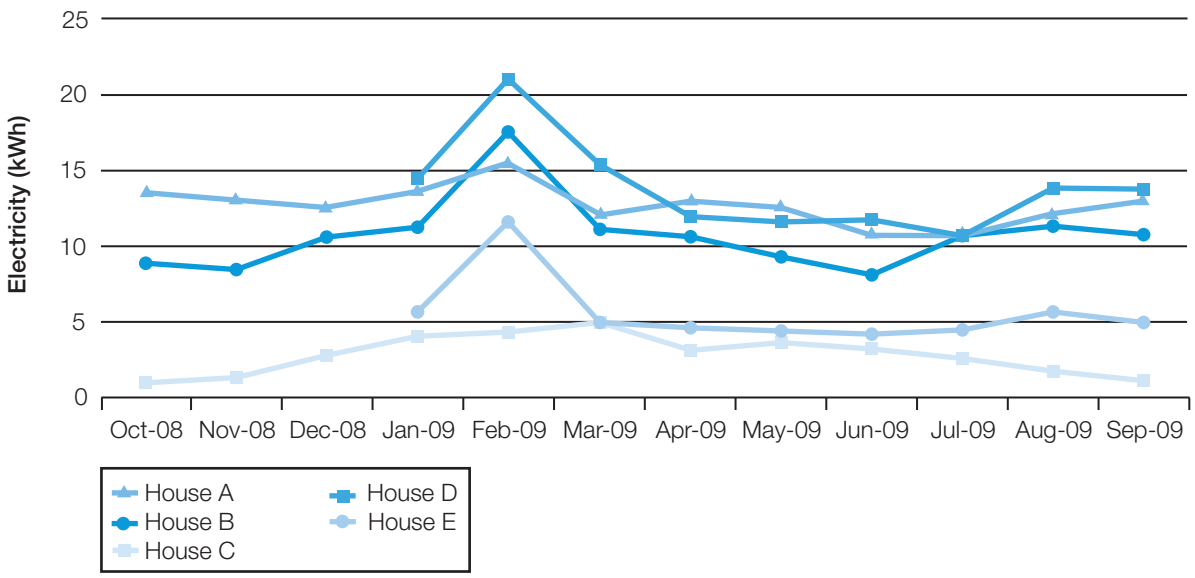
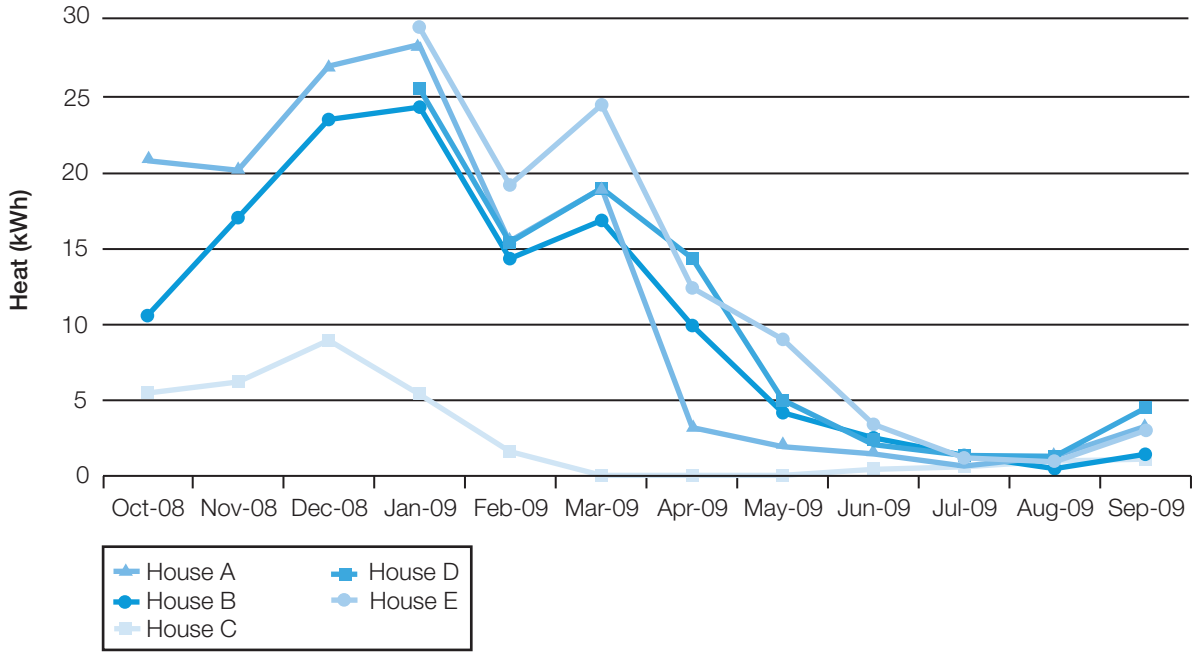


Figure 23: Mean daily communal heat input to dwellings by month



Clearly, the relationship between residents and their home is a very complex one, particularly when there is a conscious desire to reduce energy consumption. In this case, it appears that the model the resident had about consumption was particularly important in determining the control of space heating and operation of appliances. This is an interesting illustration of the use of what Kempton and Montgomery (1982) refer to as a 'folk model' of energy consumption that seeks to make sense of a complex environment by using past experience coupled with garnered information from many different sources (both formal and informal). Such models are efficient because they simplify decision-making and are influential in the way people understand and quantify consumption. The interplay between such models and the way they affect the performance of well-insulated dwellings needs to be examined more carefully if energy and carbon savings are to be realised.

The way the interactions are influenced by cost is also important. In this case the resident went on to say:

> *As for the heating and the solar panels … I was just astonished. It doesn't cost anything; it's brilliant! Well it does, but nothing in comparison. I don't need to feel guilty about turning the heating up. Because living with my parents, my dad insisted that you only turn the heating up if it's the third Ice Age. You wear a jumper, you get a hot water bottle.*

Such a response to high heating costs is not uncommon and it is here that properties such as Elm Tree Mews provide a positive message about creating living spaces that can be maintained at a comfortable temperature and at an affordable rate. The extent to which a 'take-back' or 'rebound' effect is created when improved efficiency reduces the cost of warmth (the commodity provided by space heating) is not clear in the monitoring data. Also one needs to be mindful of the impact of potential tariff increases that could destroy the current cost and affordability experience. This is particularly so in a communal system such as Elm Tree Mews where the initial heat tariff is based on assumptions about communal system performance as well as bulk fuel tariffs. In addition to the potential for bulk fuel tariff increases, the potential exists for an increase in heat tariff to reflect actual, as opposed to estimated, heat pump efficiency (CoP).

Water heating

Access to hot water on tap whenever required is seen as a basic requirement of any dwelling and as technology has improved our expectations have been raised accordingly. Yet this requirement demands significant energy inputs. Elm Tree Mews provides an interesting example of an attempt to reduce this energy demand significantly through the interplay of a communal ground source heat pump, solar panels and electric immersion heating providing heat at different temperatures. Using these three technologies together presents a difficult challenge since it adds considerably to control complexity.

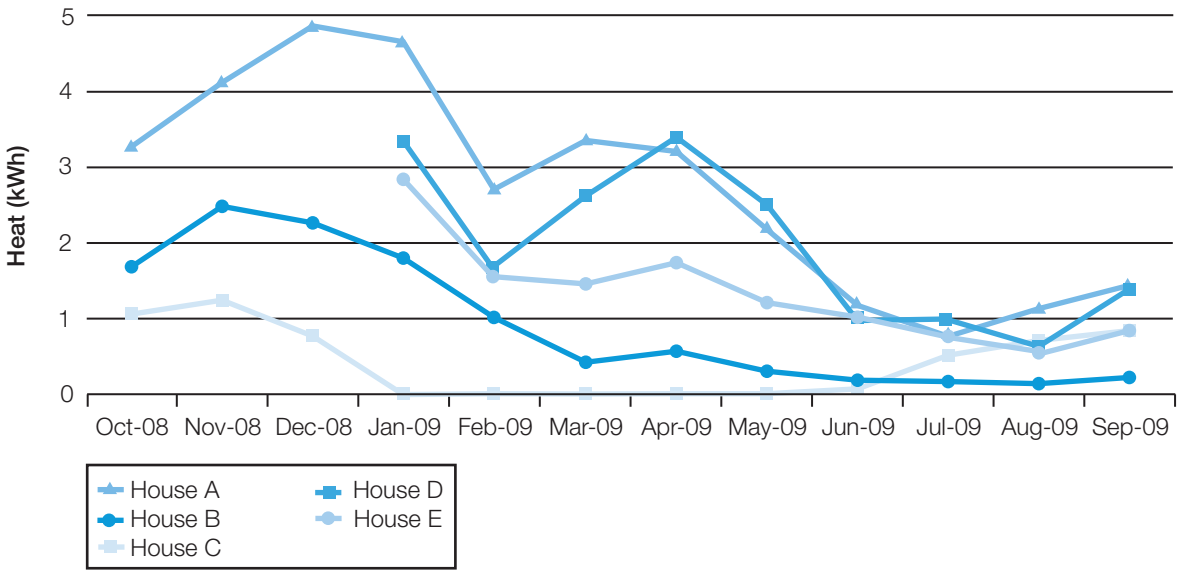
Domestic hot water consumption data is difficult to interpret fully because of a number of installation and commissioning difficulties with the solar water heating systems, some of which were not rectified until July 2009. Difficulties arose also over the reliability of some of the data from the heat meters for the solar circuits and this created another confounding factor. The combined effect of these problems meant that reliable data from a fully working system was available from only one dwelling (House B). The lack of reliable data from the solar systems created difficulties in undertaking detailed analysis of hot water energy data or drawing detailed conclusions about the relative contributions from each heat source. Reliable data is available for immersion and heat main energy but usage patterns would have been distorted by the particular difficulties with the solar systems. As a consequence it is difficult to determine the levels of consumption that would have occurred if the solar systems had worked effectively throughout the monitoring period and reliable data was available in all cases. The key issues relating to water heating are discussed below:

- Water consumption, which is the prime determinant of hot water energy, was broadly in line with the assumptions in SAP in three out of the five dwellings (Houses C, D and E) at some 145 l/day for House A, 111 l/d for House D and 49 l/day for the single occupancy duplex flat (House E).

- In contrast, House B used only 75 l/day compared with a prediction of 163 l/day, suggesting a relatively cautious approach to hot water use. As the resident noted:

  It's just during the winter, we've just got into the habit of knowing that there's hot water available in the morning and we know roughly how much we use or if it's a day that you want a shower, you know that you're going to have a shower and that's where you're using the water. You just get into a habit of knowing what you're using your water for and roughly [when].

Figure 24: Daily mean delivered heat to hot water from heat main by month



It is interesting to note from the interviews that this household was in the habit of boiling a kettle to provide hot water when the cylinder ran cold and this may have contributed to reduced hot water consumption.

- The intermittent occupation of House C reduced average consumption to only 19 l/day, some 44 l/day less than SAP would predict.

- A monthly analysis of consumption indicated that, with the exception of House C, hot water consumption fell by about 30 per cent during the summer period.

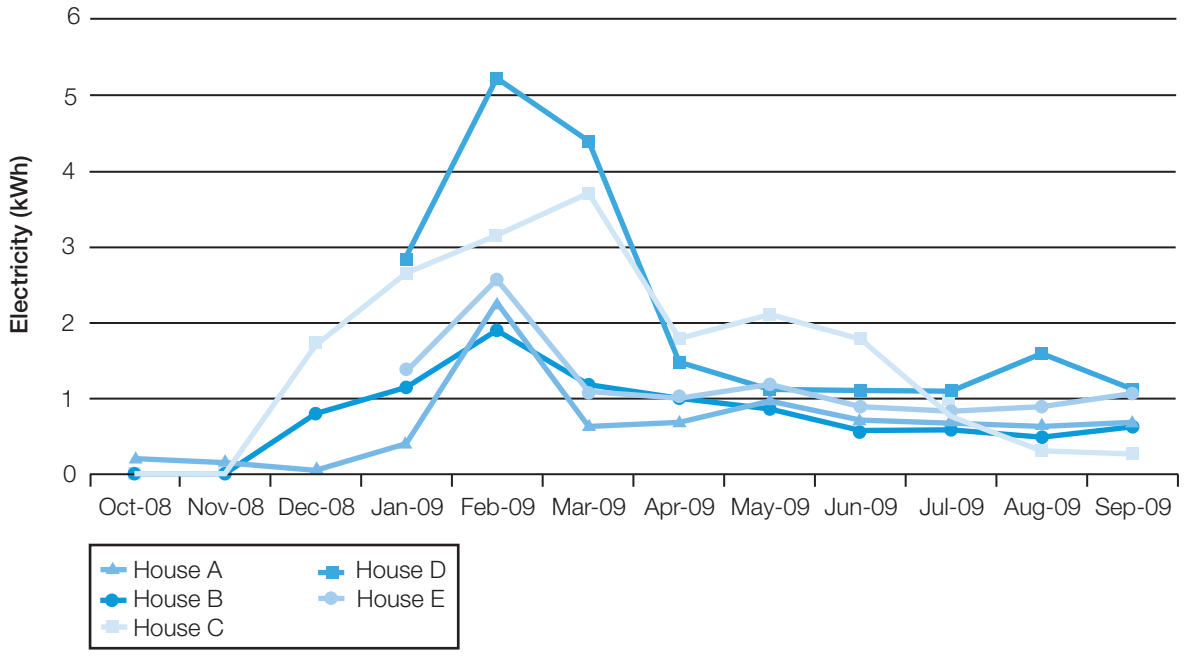
- The pattern of heat input from the heat main (Figure 24) was consistent with both the reduction in hot water usage in the summer months and the benefit of increased solar energy in the summer.[32]

- The differences in heat main input between dwellings broadly reflected the differences in hot water consumption with House B, which had a particularly low hot water usage, showing lower heat main input.

- Immersion heater usage in three dwellings (Houses A, B and E) became relatively constant from January 2009 (ignoring the impact of the heat pump problem in February, see Figure 25). In the case of Houses A and B there was a distinct uplift from the period prior to January. The uplift and constant picture are almost certainly due to the introduction of an automatic weekly legionella pasteurisation cycle, which used the immersion heater to boost the water temperature. The need for the pasteurisation cycle is discussed in Legionella protection below.

- The higher immersion consumption in Houses D and C can be linked directly to particular problems with the solar systems in both houses and to a control problem with the heat main in House C. It is interesting to note that in House D the householder believed that the solar system was working (which it was not) and was pleased not to have used the immersion much. When researchers discussed the high immersion heater consumption with the household, it transpired that the children were using the

Figure 25: Daily mean electric immersion heat to hot water by month



immersion because in their previous home they had to do this to be able to get reliable hot water when they wanted to take a shower.

- Despite the difficulties with the solar systems, the available data for the only dwelling that was free from installation problems (House B) enabled us to make a reasonable estimate of annual solar input. This gave total annual solar input 1,179 kWh, a value that accorded well with the estimate of 1,180 kWh/annum from manufacturer's data and the SAP estimate of 1,097 kWh/annum. Energy input from other sources (heat pump and immersion heater) in House B was only 626 kWh, which, because of the low hot water consumption in this house, was only 30 per cent of the total non-solar input estimated by SAP. The total heat input was 1,805 kWh, which means that for this household the proportion of carbon free heat from solar was 65 per cent compared with the SAP estimate of 30 per cent.

Internal living conditions

The investigation of internal conditions focused on the delivery of internal temperatures, the potential for overheating in the summer, and internal air quality and ventilation observations. The results of a detailed analysis of the data can be summarised as follows:

- With the exception of House C, which was intermittently occupied, internal temperatures (Figure 26) were broadly in line with those typical of UK housing. House B displayed an average winter temperature (19.7°C) just over 1°C above the SAP assumption of 18.5°C and House A just over 1°C below. Houses D and E were between the two for the part of the winter monitored.

- Inevitably there was variation in main living room temperatures between dwellings, with House A living at around 17°C and House B at 22°C. However, the most critical temperature issue was the distinct difference between the ground floor hall and toilet zone in the terraced houses and the rest of the house. The difference could be as high as 5°C (see Figure 27, House A).

Figure 26: Monthly mean internal temperatures

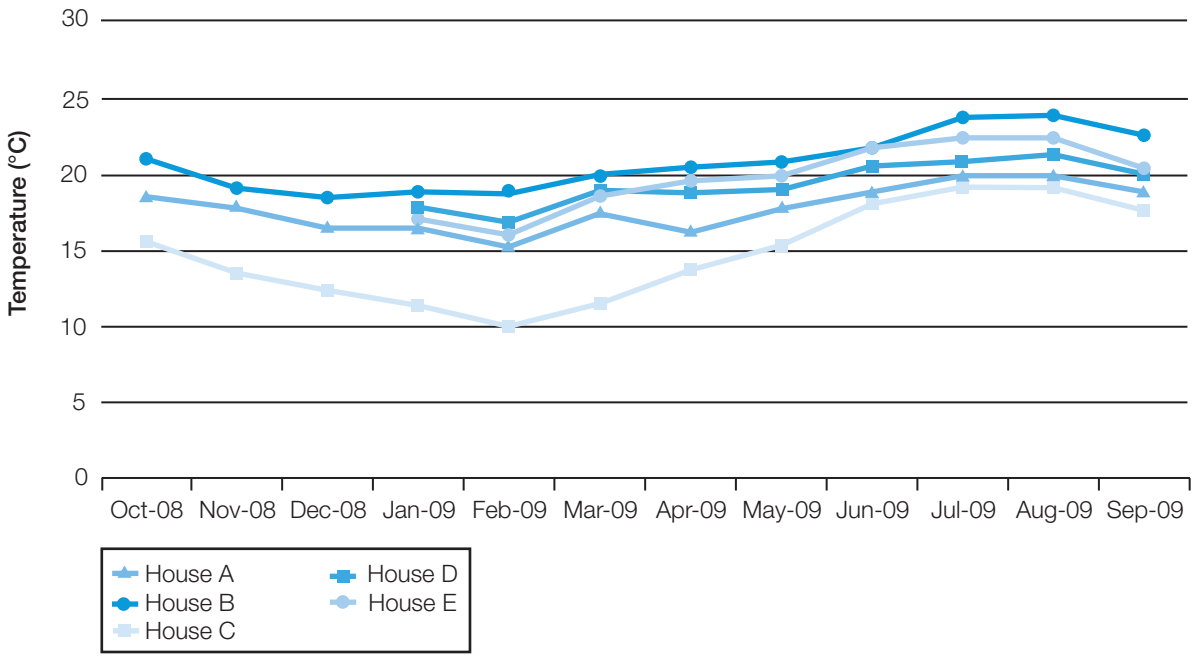
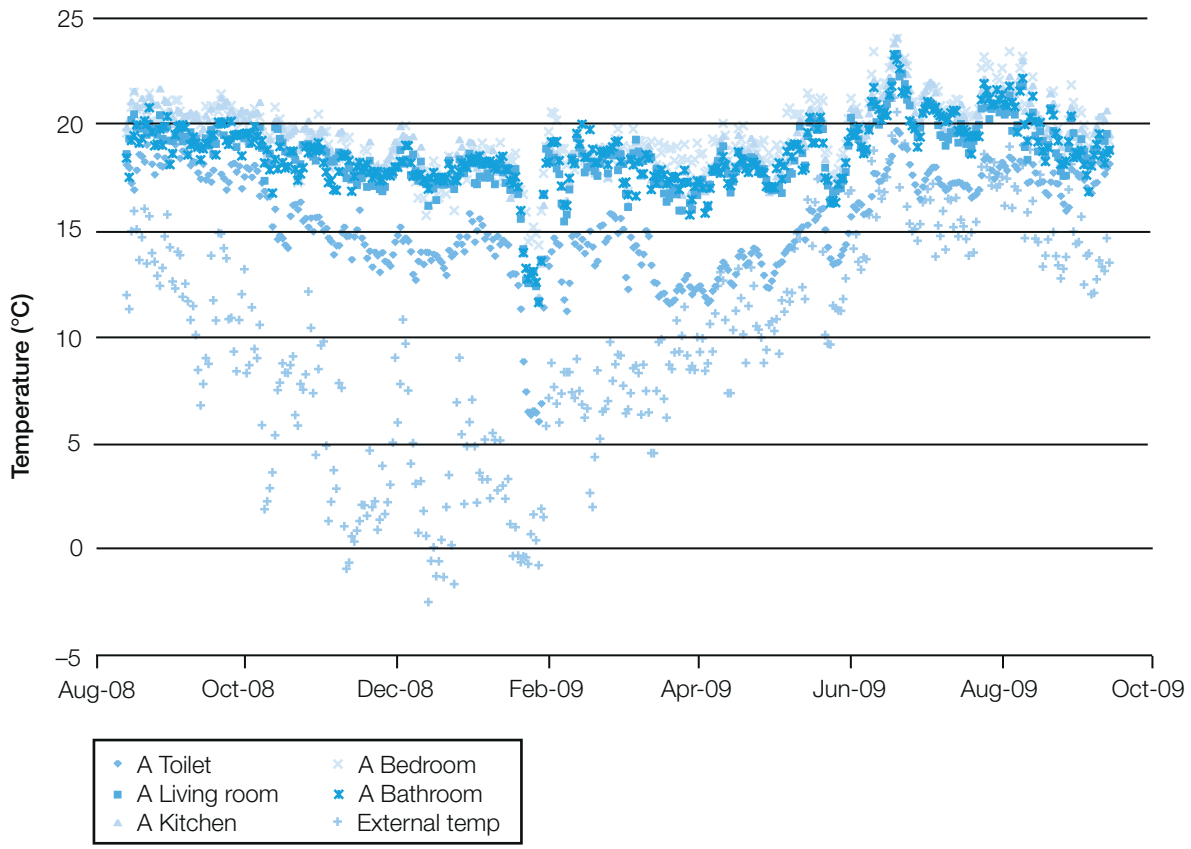


Figure 27: Daily mean internal air temperatures, House A



- The cold hall and toilet zone were commented on by all residents in the terraced houses but they felt powerless to improve the temperature. The problem was traced to the fact that the thermostat for the hall and toilet heating zone was located on a wall in the living area adjacent to the main heating controller. It would have been impossible for the residents to have any proper control over the temperature in the hall zone as it was responding to the temperature in the living room.

- The summer of 2009 was not a particularly hot one and, as a consequence, exceptionally high internal temperatures were not observed. However, for a two-day period in July 2009, external temperatures rose, peaking at 29.3°C on 1 July. Internal temperatures in the top floor bedrooms of House E reached almost 30°C. Resident interviews did not highlight overheating as an issue, although the resident in House E pointed out that some evenings were very warm and it was necessary to open both windows and patio doors to cool down. Given the lightweight nature of the construction, the small amount of evidence suggests that there may be a tendency to overheat but this is by no means certain. Further work would be required in the future to assess this possibility. This issue is likely to become important during the lifetime of these dwellings as a result of climate change and adaptation works, particularly the installation of passive night-time cooling, may be required in the future.

- Data on internal humidity and CO_2 suggested that in all but one of the dwellings (House B) ventilation rates were generally in line with modelling expectations and that the chosen ventilation strategy (trickle ventilation and intermittent mechanical extract) was effective. However, in House B the ventilation rates were about half of that in the other dwellings. This would appear to be a matter of user preference and demonstrates the impact that resident choices can have on internal air quality even in dwellings that are not particularly air tight. The impact of the low ventilation rates in House B, although a matter of preference, could lead in the longer term to increased condensation and mould growth in certain areas.

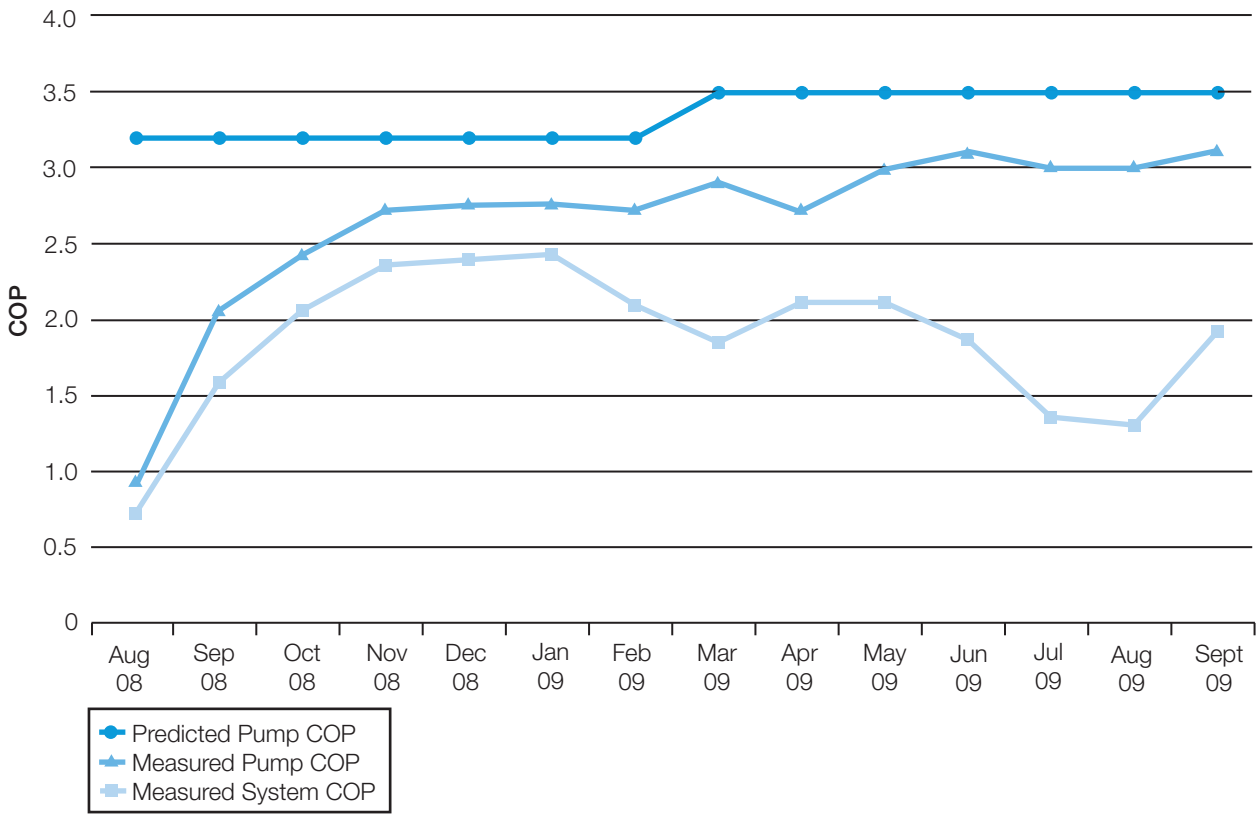
Services performance

Performance of communal heat pump

The key performance characteristic of any heat pump system is its coefficient of performance (CoP). In understanding performance, it is important to separate the performance of the heat pump unit from that of the system as a whole. In this analysis, the heat pump CoP is a measure of the efficiency of the heat pump unit in isolation from the rest of the heating system and is calculated by dividing the energy output of the heat pump unit by the electrical energy needed to run it. The system CoP takes account of other system factors such as the energy used to run the main circulation pumps and any storage or distribution losses up to the point of delivery. In the case of Elm Tree Mews, the system boundary for the system CoP was defined as the heat pump unit, all distribution pipe work and circulation pumps up to the heat meters at the point of entry to each dwelling. Monthly performance of the heat pump is illustrated in Figure 28 showing both measured pump and system CoPs. These are compared with the nominal predicted pump CoP using manufacturer's data and the assumptions in SAP. Up to February the anticipated value was 3.2 but, following a change to the internal circulation pump within the heat pump unit in February 2009, the predicted pump CoP increased to 3.5.[33]

It can be seen from Figure 28 that the heat pump did not achieve its expected performance, with an annual pump CoP of around 2.7 and a system CoP of around 2.1. Indeed, during August 2008 both the pump CoP (0.94) and system CoP (0.67) were less than 1, making the system performance for that month worse than could have been achieved with gas-condensing boilers in the dwellings. The main cause of this inefficiency was found to be the electrical energy required to drive the internal hot-side circulation pump, which was designed to run continuously so as to provide a return water temperature control signal. A number of interventions based on a continuing analysis of the data were made and, although system performance dropped off during the low demand period in the summer of 2009, the CoP did not drop

Figure 28: Monthly trend in pump CoP and system CoP



as low as in August 2008. This illustrates the strength of an action research approach, which enables interventions that benefit the system but also enhance understanding and learning.

The complex nature of the communal heating system and controls gave rise to a number of performance problems and associated inefficiencies. Many of these issues had their roots in the design of the system (including controls), assumptions about performance and underdeveloped commissioning procedures. The lack of understanding of the impact of commissioning processes on the various factors such as heat pump flow temperature settings and circulation pump set-up, led to very low efficiencies during the first few months of operation. It is unlikely that these factors would have been picked up by the Housing Trust or contractors had the research team not been monitoring the system performance and at the same time analysing the data on at least a weekly basis. Indeed, under normal circumstances, the necessary meters and sensors would not have been installed and no one would have known that the system was not working as effectively as assumed during design.

Perhaps the most important strategic issue of heat pump system design was the decision to deliver heat to both space and water heating. Not only did this complicate the water heating system but it resulted in a compromise in flow temperatures. For the underfloor space heating system a flow temperature of 30°C to 35°C is preferred, delivering a floor temperature of around 29°C or less (CIBSE, 2005). In contrast, preferred flow temperatures for hot water are between 55°C and 60°C so as to provide adequate hot water (particularly in the absence of solar) and reduce the risk of legionella. In general, the lower the flow temperature, the higher the CoP of the heat pump. In the system, as-installed, the compromise flow temperature (42°C) was suboptimal for space heating, reduced the space heat CoP and was not, on its own, able to provide the water temperatures required. Also, the fixed-flow temperature prevented the use of weather compensation for space heating, which could have improved the heat pump CoP during the swing seasons of autumn and spring.

An alternative heating strategy for Elm Tree Mews would have been to use a second heat pump system to supply the hot water heat at a higher temperature but in a communal system. This would have required a separate heat main for hot water. Alternatively, it may have been more appropriate to use the heat pump to supply underfloor heating input only and to find another way to supplement the solar hot water input to the domestic hot water. The lack of any gas supply to the houses meant that the simplest approach in this case would have been to use the immersion heater in conjunction with the solar thermal system. Of course this would have forgone the potential efficiency improvements from the heat pump but would have avoided the need for a legionella pasteurisation cycle. When the potential efficiency gains from a 'space heating only' approach are taken into account, the net impact on carbon of immersion heater use may have been small. A further option could have been adopted involving the installation of individual heat pumps in each dwelling capable of supplying both heating at 35°C and hot water at around 55°C. This would have reduced significantly the need for immersion heater input and simplified the control requirements. All of these options may or may not have resulted in improved performance and, indeed, the option of single heat pumps was considered during design development. This option was rejected because of concerns about the availability of suitably sized heat pumps (the smallest available at the time was 5 kW) that were capable of achieving high CoPs at the very low space and water heating loads anticipated. Perhaps this illustrates what appears to be a general difficulty for designers of low carbon housing, who are faced with a set of problems about which there is little empirical data and few, if any, suitable modelling tools.

Heating and hot water control issues

One of the main concerns with the provision of hot water to the dwellings at Elm Tree Mews is that the combination of the three different hot water inputs (solar, communal heat, immersion) needs a complex control strategy for the system to be efficient and to provide a reliable supply of hot water. However, the measured data from monitoring of the occupied houses and feedback from the residents indicate that this

was not always achieved, particularly during the winter months when the solar input was at its lowest. At least some of the difficulties relate to the technical capabilities and accuracy of temperature settings within the control system and these are discussed in the technical report.

For the householder, the complex nature of the heating and hot water systems meant that they were faced with a bewildering array of controls including a main heating controller, hot water controller, immersion timer (including the automatic pasteurisation cycle), room thermostats and solar controller. The potential for confusion was considered by the design team, who provided a plain-English guide to the controls for incorporation into the resident's handbook. There was also an expectation on the part of the designers that some controls (the solar controller in particular) would need little or no adjustment once set up at commissioning and on occupation, thus simplifying the control array. However, whatever the design expectations and provision of information, it was clear that the communication of this information to the residents was not effective.

Legionella protection

The research team identified early on in the project that there was a potential risk for legionella contamination of the stored hot water in the dwellings as the heating system design was not able to ensure that the temperature of the stored hot water was raised to 60°C on a regular basis, as required by legislative guidance (HSE, 2000; HSE, 2003). The critical temperature range for legionella risk is between 20°C and 45°C, a range that would be likely in the winter with little solar input and heat from the heat main being delivered at between 40°C and 45°C.

Following concerns raised by the research team in April 2008 prior to occupation, the Housing Trust subsequently carried out a legionella risk analysis and also arranged for an external contractor to carry out a series of bacteriological tests on the water. The results of the initial tests indicated that there were no legionella bacteria in the water, but that general bacteriological levels in the water were higher than normal, indicating that there was some risk of contamination. To minimise any residual risk, it was decided to modify the hot water cylinders in all the houses with equipment designed to perform automatic pasteurisation cycles. These alterations were carried out towards the end of 2008 and involved a four-hour timed immersion heater cycle with the water in the cylinder being mixed using a shunt pump to circulate water from the top to the bottom of the cylinder (see Figure 29). Monitored data showed that the energy used for a typical pasteurisation cycle varied from around 4 kWh to around 9 kWh, and would be dependent upon the water temperature in the cylinder at the time of the cycle.

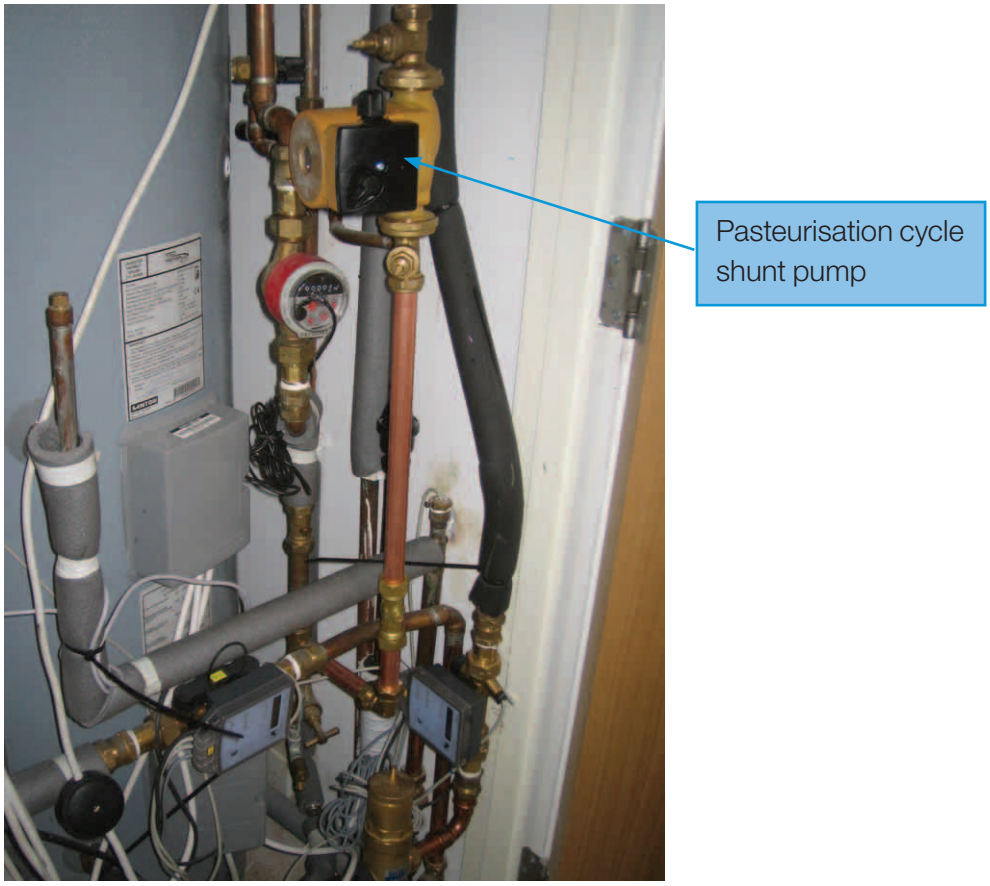
The issue of how to control levels of legionella and other bacteria in stored water will become more important in housing as hot water system designs become more complex and use combinations of low carbon heating inputs with lower input temperatures than is the norm for gas heating. It is interesting to note that some of the residents have adapted their use of hot water to coincide with timing of the pasteurisation cycle. One resident has complained that the noise from the shunt pump is loud enough to be disturbing while sleeping.

The relationship between residents and their homes

As observed at the start of this chapter, a key focus of the study has been the performance of the dwellings following occupation by the residents. The data analysis examined in the previous sections has shown that the performance of the various energy systems in place in the dwellings has been mediated by the residents using them, highlighting the importance of taking the relationship between residents and systems seriously. This section of the chapter provides a more discursive examination of this relationship and considers what it means for policy and practice in low carbon housing supply.

Figure 30 sets out the four key themes that can be drawn from the analysis of the quantitative data and the qualitative interviews. The themes are: design and resident needs, engaging with new

Figure 29: Cylinder cupboard showing installation of shunt pump



technologies, knowledge and confidence, and affordability. As the diagram suggests, these themes are not mutually exclusive and tend to be interconnected. In addition, the former two themes are more clearly measured, whilst the latter two are less tangible but nonetheless important. This highlights the problems of understanding how humans with various behaviours interact with a building.

Design and resident needs

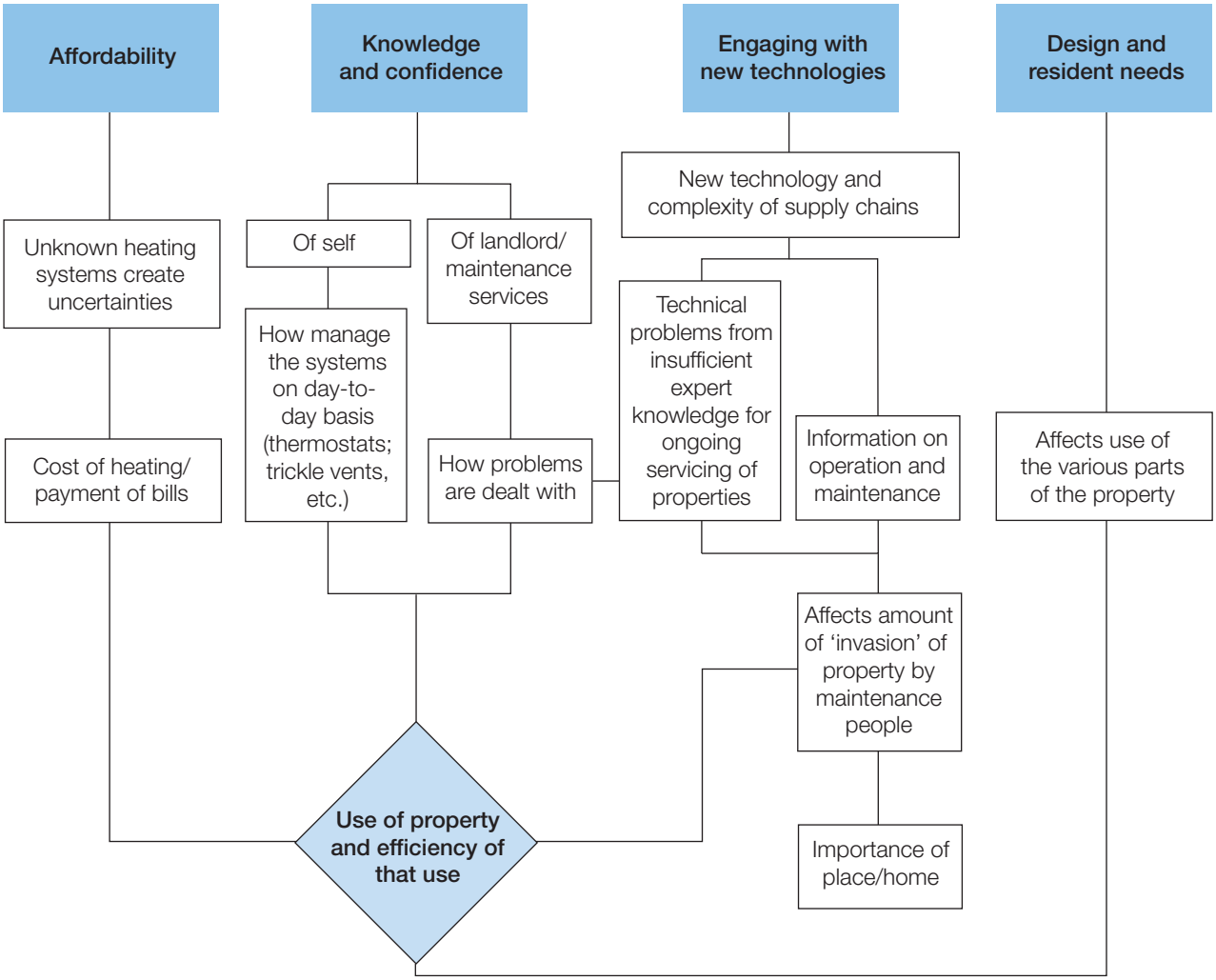
All aspects of performance are important and the design task is a complex one involving many design standards such as security, wider environmental impact and lifetime-home requirements, as well as important aesthetic considerations. While this research project is focused on energy and carbon performance, it is important to recognise this wider design context. However, a crucial element in the success of any dwelling design relates to how it affects the lived experiences of those who occupy it. The critical concern about any lifetime home such as Elm Tree Mews is that the design will accommodate the changes in lifestyle over time and still provide the same utility value needed by the household.

For example, using the loft space to provide additional living space was an interesting design feature, but in practice it removed valuable storage space. This lack of storage space was a common complaint from the residents, and was particularly an issue for families, as one female respondent pointed out:

> *The other house had a loft, an attic, so, I mean we could put all our stuff up there, where as this one doesn't have any of that.*

Similarly, the usefulness of the indoor 'winter garden' space,[34] which is illustrated in Figure 31, was questioned by the residents of the mid-terrace properties. As one male tenant pointed out:

Figure 30: Emerging themes from resident interviews



> *You can't use it because there is no heating in it. We just use it as a dumping bin at the moment because you can't sit in it. You can't use it as a conservatory sort of thing. There's no heating in it. And it takes up [space], and the garden's very small anyway. It takes up a massive lump of the garden … If they came in and said, 'We're asking people, would you have that or would you not?' I would say 'Knock it down. Today'.*

Another resident pointed out that the winter garden would be used more if the temperature was higher. Indeed, he noted that it might be useful as a family dining space rather than use the existing combined lounge and dining area. However, the solution that the resident is considering is less than ideal in a low energy home:

> *We have got a little kilowatt heater that we got over the winter and [we might] use that to warm it up in there before we have dinner and then we can use it.*

Spaces and design have to work for those who live in them, otherwise the residents will adopt solutions that often negate the positive effects that the designers have provided, such as heat and insulation. It is worth reminding ourselves that sustainability is a human-conservation term and this is particularly pertinent when contemplating the homes we create. They must provide a living space that is sustainable in terms of their usage as well as their construction and appliances. If care is not taken then all the effort to preserve heat and minimise energy use will be to little avail.

For example, residents felt that they did not have a suitable inside space in which to dry clothes on wet days or during the winter, and this was exacerbated by the lack of radiators, which, in their previous homes, they used to dry clothes. Indeed, the main use of the winter garden (apart from being a general storage area) was as a drying area, with residents putting up clothes-horses to dry their washing. A number of residents had either purchased or were considering the purchase of a tumble dryer to ease the difficulties of clothes drying. The apparent conflict between the low energy objectives and the need to increase energy consumption in order to dry clothes was noted. As one resident put it:

> *we're supposed to be saving energy but we have no way of drying clothes now so we have to have a tumble dryer. Because in the other house we had radiators so in the wintertime the big things went in front of the radiator to dry your clothes. We can't do that here. So it's all defeated itself. The saving that you were getting there you're now losing because you've got the tumble dryer.*

The availability of drying space is a key need for households with children who need to do a wash each day compared to the single person households who were washing once a week. The concern about access to drying spaces is a significant one when families are expected to be able to dry a wash daily throughout the year. The purchase of a tumble dryer is an obvious response, but one that will increase appliance energy consumption and carbon emissions.

Engaging with new technologies

To a certain extent, many of the concerns raised in the qualitative interviews were of the type that could be applied to any form of housing. However, low carbon housing of this sort introduces residents to a new

Figure 31: Winter garden on south façade of end-terrace house

Winter garden

Floor plan

set of systems of which they are unlikely to have any experiential knowledge to draw on as a guide. One female tenant explained: 'I switched everything off the other day and I probably turned something off that I shouldn't have done … It's a bit like *Dr Who*, you know [with all the buttons].'

In the case of Elm Tree Mews, resident feedback indicated that the operation of the heating and hot water controls was very confusing. The potential confusion is demonstrated in Figure 32, which shows the four main heating controllers in the dwellings, all of which have different displays and approaches to their operation. Residents need to feel that they are in control of their property and can manage it on a day-to-day basis. This lack of clarity reduces the sense of control felt by residents and their confidence in and contentment with the property. In terms of the property's energy and carbon performance the confusion over controls is likely to result in residents not being able to use their homes effectively. Among residents, there were obvious concerns about the lack of technical knowledge of how things function and what to do to put them right.

This system has been further complicated by the thermostat controls, which are the only part of the heating system that is reasonably familiar. Since the operation of the heating and hot water controls

Figure 32: Heating system controls

is very confusing, several of the residents used the thermostats to control their heating in preference to the programmer, an approach that is not uncommon in other households. However, the thermostats themselves were an added source of concern for the residents. The controls, which appear in most rooms, do not have any numbers on them and residents pointed out that setting them at an acceptable temperature (around 20°C) was a matter of guesswork (see Figure 33). This has led to unnecessary frustrations. As one tenant's discussions with a plumber, who visited the site, indicates:

> *The plumber came and he says to me, well we work them [the heating timer] on these hours and … you just set them [the thermostats] all at 20˚ … I said 'Well you show me where … 20 is then and I will.' Then he looked at [the thermostat] and went 'Ooh well I think it's about there.' … but it could be 30˚. I don't know.*

An attempt to remedy the confusion with respect to the thermostat setting was made by the Housing Trust and an illustration showing the corresponding temperatures on the thermostat dial has been provided in the Home User Manual. However, it must be acknowledged that the provision of information in this way is likely to be a much less effective means of communication than a well-designed thermostat dial. Crucially, the heating and hot water system was complex enough without seemingly simple technology, such as a thermostat, being difficult to understand and adjust. It also raises a more fundamental question about why such controls are used generally in the construction industry when they do not provide residents with information in a way that enables them to exercise effective control over their heating system.

Knowledge and confidence

Being in control is important to people and their sense of well-being. As suggested in the introduction to this chapter, 'home' is the site where people can feel in control of their space (Seamon, 1979; Cresswell, 2004) and when this control is disrupted it is likely to have an impact on how rooted and content they feel with the property. Having the knowledge and confidence to make use of the dwelling in terms of heating, energy and ventilation affects your control over the internal comfort of the dwellings. With rented properties this confidence is not only in your own understanding of the heat and energy systems, but in the capability of the landlord and their maintenance services to deal with this new technology correctly.

Figure 33: Room thermostat dial at Elm Tree Mews

Mention has already been made of the variation in the internal conditions within the different dwellings. However, to what extent does this relate to resident needs and desires or is it a reflection of their lack of knowledge of and confidence in the use of control systems? Clearly, to tease out such relationships requires purposive testing on a micro scale, and beyond the scope of even this detailed study. However, there are some general themes emerging that suggest that such a micro study might be worthwhile.

The interview evidence would indicate that understanding of the heating system appears to affect how confidently residents use the systems and, as might be expected, how effectively they use them. An example of this is the use of the thermostats in the dwellings. In a couple of cases the thermostats were left at their original settings by residents or were only changed in response to the research team or the maintenance people suggesting a change be made.

> *It's been okay … because I didn't know how far to turn them up without it costing me a fortune … so I left them. It was warm, but it could've been warmer, but I didn't know what to do so I just left them.*
>
> (Female resident with family)

Whilst in another case, this lack of knowledge and understanding led a resident to set the room thermostats upstairs at a higher temperature than that set on the central heat main controller.

> *What I tend to do is I tend to change the thermostat on the unit itself the main one saying what temperature I want it at … If I change these thermostats downstairs … I feel it's like it helps turn the heating off quicker. Although that's not a problem downstairs … we still want the heating on upstairs. So I tend to keep the thermostats on the walls as they are quite high, trying to help, especially during the winter to get it nice and warm upstairs … I have it set at 27, … I have it set at that to try and get it to get hot quicker.*
>
> (Male resident with family)

Similarly, in terms of ventilation, several residents were unaware of the trickle vents and how they worked and, as a result, they had not been used: 'I didn't know what they were so, I thought, I'm not touching them.' (male resident with a family). Instead, windows were opened when the dwellings got too hot or stuffy, rather than using a more measured ventilation of the properties, which the trickle vents were designed to provide.

Finally, the complexity of this relationship between knowledge and understanding is made clear when the need to incorporate housing association services and maintenance staff is required. Such involvement means that not only is the control of one's property passed on to a third party to resolve an

Figure 34: Shower in en-suite bathroom

issue, but lack of knowledge and understanding among the maintenance staff means that this 'intrusion' into the private space of the home is increased as the problem reoccurs. This can affect how residents feel about their 'home' and how they subsequently report problems.

A good example of how this intrusion has an effect on the way residents feel about the properties is the showers on the second floor. The doors to the shower cubicle in the en-suite bathrooms in the houses and duplex flat were a source of bewilderment and frustration to the residents. The showers were designed to be accessible for those with a disability and consequently the shower doors were of half height (see Figure 34).

The householders all noted that the showers leaked and asked for the doors to be replaced. However, it took a number of visits across a long period of time for the problem to be resolved because the type of shower unit being used was innovative but not functioning properly. The effect on residents was one of frustration, as one resident noted:

> *Four months it took them to get that [fixed]. We couldn't use that shower for four months. Now, I don't care who you are. Now, that is ridiculous. And in the end after four months, they suddenly decided, that they would put a normal shower cubicle in. So we said to them, why didn't you just do that in the … first place?*
>
> (Male resident with a family)

Affordability

Linked very closely to this idea of knowledge and confidence is that of affordability. If low carbon housing is to provide dwellings that offer low income households an affordable roof over their heads, then it has to be clear what energy savings can be made and how systems can be run to maximise this efficiency. Uncertainties about the cost consequences of different approaches to space and water heating control will affect how residents use the systems. As noted in the introduction, how people use a property relates to their own set of personal circumstances and their understanding of the property.

Residents, on the whole, were pleased with the low bills for delivered heat energy (space heating and part of the water heating). These relatively low bills are a positive outcome for this set of dwellings, as one happy tenant observed:

> *Our last two bills [summer heat meter bills], which come to us monthly: one was £1.26 and the other was about £1.50 … I loved them, they're fantastic. When we first moved, we got a payment card for them to help keep track of payments and stuff and I'd go down and I say 'Can I have £1.26 on this?' And the guy looks at me as if he hasn't heard me right.*
>
> (Female resident with a family)

In interpreting this comment it is important to remember that these bills relate to those for heat supplied by the heat pump in two summer months and would be dominated by hot water, which is also heated by the solar panels and by the immersion heater. As the cost analysis above demonstrates, space and water heating, from all sources, averaged over the year, was around £18 to £25 per month, across the scheme. In some cases, there were concerns about the electricity bills but, as the cost analysis shows, electricity bills are dominated by the use of lights and appliances, which are a function of ownership of appliances and their use rather than the design and construction of the dwellings.

Low-income households have to keep a tight rein on their finances, particularly if they are on benefits, and this can mean that even with low bills for space and water heating they may still feel that they cannot maintain their property at a comfortable level:

There's no heating on in here and that's because I can get away without it being on. But realistically it should be on but I daren't put it on because I don't want to have to pay for it. I'm sorry, that's just how it is.

(Male resident on benefits)

Several residents also showed concern about the problems of insufficient hot water and how this can lead to a lot of unnecessary energy and water wastage:

I've had quite a few cold baths. Well, nearly cold baths. And I suppose, even though they've put an immersion heater on, and there's a timer apparently on it, I keep switching it off cause I kind of feel it's the complete opposite to what they [the dwellings] were originally built for.

(Single female resident)

It's meant to be eco and save water; but it can take a … gallon to get the hot water to come through. So you've wasted all that water in the shower just waiting for it to come through. Whereas an electric shower heats it [snap of fingers] there and then … The immersion heater, if you leave it on, will heat the water to a certain point then stop and then heat it up again. So there's things in the house that have defeated the object.

(Male resident)

Overall, the affordability of these properties is critical since this is the tangible outcome for residents; it is the one area that they can see measurable differences between this type of housing and traditional structures. For social landlords to provide the additional investment required they also need to see a tangible benefit to their tenants. This needs to work for all income levels, but particularly for those on low incomes, if it is to provide a viable option for social housing providers in the future. However, it is not clear from the data whether, in the case of Elm Tree Mews, there was a significant 'take-back' or 'rebound' effect as efficiency improvements reduced the cost of warmth.

Understanding the relationship

The relationship that residents have with their properties is highly complex and understanding this relationship is critical if we are to design and produce low carbon housing that works for a range of households now and in the future.

It seems appropriate to end this section on the resident experience with a useful quotation from one of the residents about where all this should be leading us:

It's not just that I've cut down on the amount of energy that I use; I try to plan ways of making do with less. And I think that's what we need to do. We don't just need to cut down a little bit, turn down our heating by one degree, recycle a bit more. We need to reassess how we are living our lives and create a plan.

(Female resident)

What is suggested here is not simply the occupation of better housing, but a qualitative shift in attitudes and behaviour. As the chapter has shown, people use their homes in a variety of ways, have different needs and different feelings with respect to comfort and amenity, which, in turn, affect the overall performance of the dwellings. Understanding the complex relationships involved is of paramount importance if dwellings are to be designed that support low carbon living. Failure to address the resident–dwelling relationship is likely to lead to disenchantment. As another female resident put it:

> *I think you can soon be made to feel disenchanted with the whole thing. You don't think what's the point but you do feel that it can easily become a façade where it looks good but you're not actually putting things into practice and they're not working so is it doing any good? And I think then you become a bit … I suppose you just feel disillusioned a bit.*
>
> (Female resident)

The findings in this section suggest that if we are to tackle the issues of living in low carbon housing then there are two key concerns that need to be addressed. The first of these is the need to understand the complex relationship between property performance (in terms of heating, ventilation and energy) and the people who live in the properties through careful systematic longitudinal monitoring at a micro scale to see whether designs stand up in the face of resident use and need. Secondly, we need a corresponding understanding of the extent to which information and advice affect the way people use their properties and make informed decisions about their energy consumption. This study and similar ones undertaken by the research team have indicated that the nature of the information provided about ventilation, heating or managing energy within a home affects how people understand their homes. This, in turn, will affect their understanding of how to go about reducing their carbon footprint.

5 Issues for the development process

Responses to the underperformance at Elm Tree Mews could be either to dismiss the experience as a one-off (one of those jobs that did not go to plan) or to conclude that the technology employed does not work. Both responses would be wrong. Similarly, the discussion could focus exclusively on the narrow technical questions and ignore the broader processes that gave rise to the outcome observed. As we discuss in Chapter 6, evidence of energy and carbon underperformance in new house building is mounting and concerns are being raised about the achievement of low and zero carbon standards. Many of the technological and process problems observed at Elm Tree Mews echo those observed in the Stamford Brook development and other schemes that employ traditional masonry cavity construction. The conclusions of the Leeds Met research team at Stamford Brook were not that the technologies were wrong or that the observations were isolated incidents, but that the cultures and processes that pervade the development of new housing, from master planning through design and construction to our understanding the needs of occupants, have a long way to go if they are to deliver low carbon homes. Our study of Elm Tree Mews has reaffirmed this.

The procurement process

The initial procurement of the design followed a conventional architectural competition. Given the observations on performance in Chapters 3 and 4, it is interesting to observe that the brief identified quality as one of its 'Key Considerations' (JRHT, 2005). The following quotation from the competition brief (under the heading 'Maintaining Quality') sets out how the authors perceived the quality issue.

> *The four core stages of planning, design, construction process, and finished product represent critical links in the supply chain; therefore, demonstrating how sustainability objectives can be maintained along this chain is critical. These stages face other challenges such as skill shortages (the Egan Reports of 1998 and 2004 highlighting both construction skills and planning delivery issues respectively), and the evolution and role of modern methods of construction/off-site manufacturing. Hence competitors must incorporate reliable construction proposals with their bids.*
>
> (JRHT, 2005)

An analysis of the description in the quotation above would suggest that the strategic components were in place to enable the assessment of entries in terms of their delivery of sustainability and other objectives.

The references in the brief to core development stages, the overall supply chain and the submission of construction proposals all demonstrate a strategic understanding of the importance of evaluating process and proposed construction. This is reinforced by the requirement, in another section of the brief, for a:

> *final design and sustainability statement setting out the approach taken, philosophies and processes underpinning it, and how it addresses the three key considerations.*
>
> (JRHT, 2005)

The statement was to include, among other things, information on the preferred construction techniques and to:

explicitly identify the sustainability aspects and features of the proposals, particularly its environmental legacy contribution and other factors such as energy efficiency, embodied energy used in construction, water use proposals, pollution minimisation, materials optimisation … and positive responses from a health and well-being perspective … What is its environmental footprint?

(JRHT, 2005)

Despite the strategic understanding of the importance of process and technical proposals there would appear to have been no explicit requirement for objective data on the performance of the proposed construction, nor was there any requirement for proposals to demonstrate how performance would be assured. The fact that the winning design submission does not contain any supporting monitoring data or other evidence of actual performance is unsurprising. It is rare for houses and housing developments to be measured (post-construction or in-use) or, even where monitoring has taken place, for the results to be placed in the public domain. Given this position, it would have been unrealistic for the selection processes to have required performance data, which, in any event, would not have been available. The problem faced by the selection panel and by others procuring new housing is that they have to rely on design assumptions and generalised projections that have little in the way of objective as-constructed performance data to support them.

Despite the difficulties created by the dearth of performance evidence, it is arguable that in making procurement decisions clients could require design and construction processes that include a higher degree of testing and performance assurance than was evident at Elm Tree Mews. Indeed, as the UK seeks to achieve its zero carbon homes target by 2016, it will become increasingly important for designers, developers and contractors to demonstrate that their designs are robust and will deliver the promised performance. The development of a regulatory system that encourages and supports such an approach was recommended in a recent government-sponsored report by the Zero Carbon Hub (ZCH, 2010; Bell, *et al.*, 2010a). The role of social housing clients could be very important in developing the systems that would support such regulatory change. Of course it must be acknowledged that to make such demands, in the current climate of industry practice, would be difficult and could result in significant cost increases as contractors sought to cover their risks.

Complexity

The whole procurement process was a complex one, with over 20 different organisations and roles, all of which needed to interact and communicate. Figure 35 shows the project organisational chart. It is apparent from the large number of relationships shown that the organisational and communication demands were considerable. In particular, the relatively high number of companies involved in the design, supply and installation of the heating and hot water system had the potential to give rise to issues with communication and final performance and placed considerable pressure on project management, specification and commissioning procedures. Many of the problems with the operation of the solar system could be linked to the management of the design and installation process and the communication among the participants.

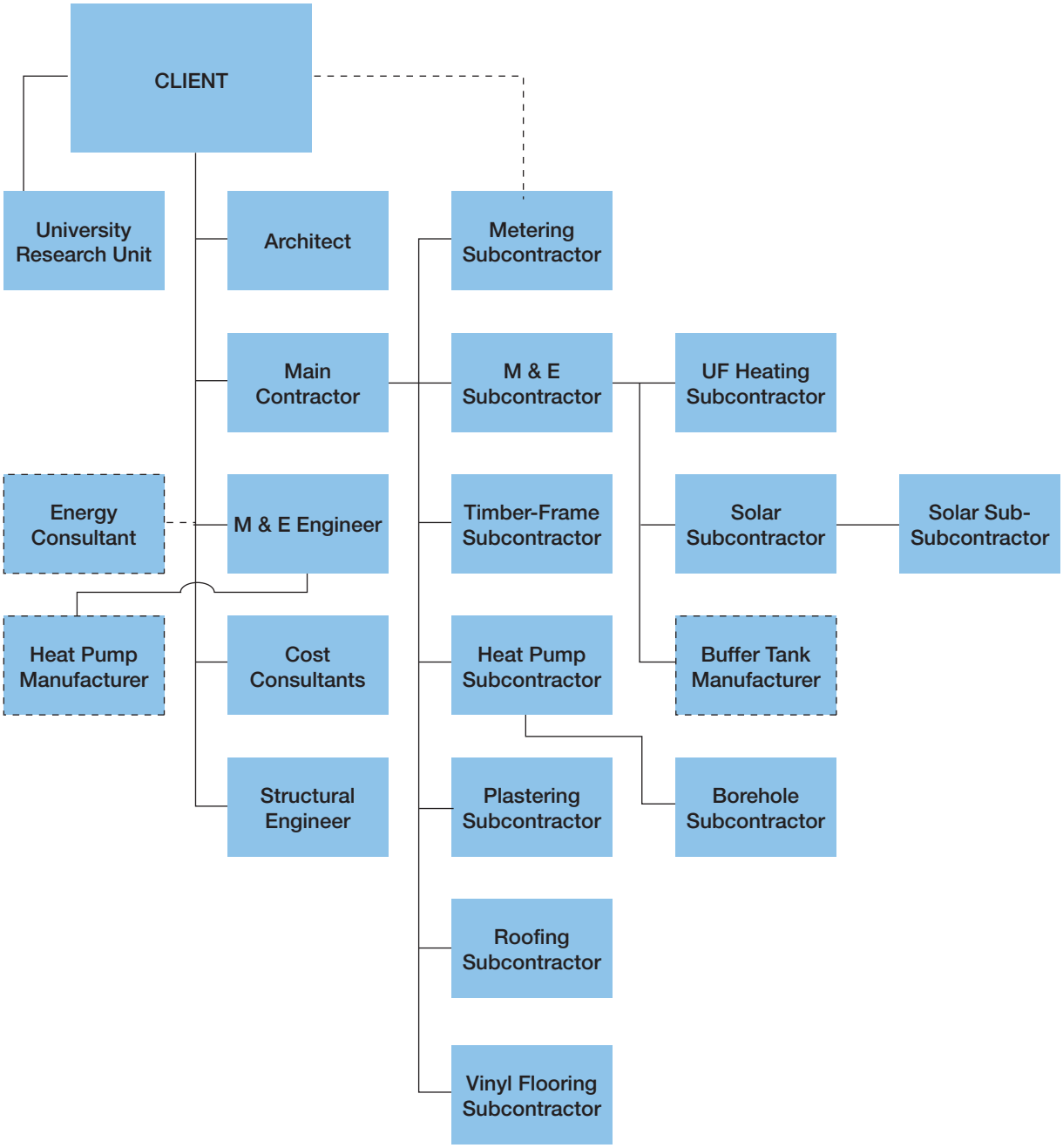
The main M&E contractor installed the pipe work between the panel position and the cylinder cupboard as well as the solar cylinder and heat main feed. The solar installer fixed the panel, solar pump and solar control system and connected the pipe work to the panel and the solar coil in the cylinder. When the solar installer came to complete the installation there were difficulties in deciding which pipe was flow and which return and which control cable went to which dwelling. Also, no one had any knowledge of the existence of kinked pipe work.

The problems identified are more likely to be systemic rather than matters of individual culpability. It is likely that the main M&E contractor used what was thought to be appropriate pipe material (presumably with no knowledge of the existence of specialist materials) and the solar installers did their best to work out what was flow and return and where the cables went. However, for the system to work reliably, the need for communication of detailed and precise information was acute. Given the separation of functions

and underpinning knowledge, the risk of error was high. The risk could be reduced by a redesign of both technological detail and the processes of installation. Suitable products are available for solar installations that combine flow and return pipes and control cable into a single pre-insulated dual pipe, which is less prone to kinking. The combined nature of the product minimises the risk of mixing up the flow and return pipes and control wiring. Similarly, making the solar subcontractor responsible for the installation of the pipe work might also have reduced the risk of installation problems.

The complexity of the procurement system tended to diffuse responsibilities overall and it was difficult to identify a single level of overall responsibility for energy performance. The complexity and coordination of the solar system is one example, but others relating to ensuring that U-values were as specified or thermal bridging was handled effectively and checked, tended to fall through the cracks in the system. Ultimately, energy and carbon performance is a function of the whole dwelling and the interaction with the household that lives in it. If responsibility for performance is divided among specialists, as it inevitably is, there needs to be some form of overarching control that will ask the right questions and ensure coordination not only to complete the work on time but also to ensure that performance is not

Figure 35: Elm Tree Mews project organisational chart



compromised. This role is not currently defined in project management teams and needs to be considered as low carbon housing design and construction processes are developed.

It must be recognised that some of the complexity was an inevitable result of the pilot nature of the scheme and the fact that the systems used for both the fabric and the services were outside the house-building mainstream. Clearly, there is scope for rationalisation, particularly of the solar water heating system. In principle, the design and installation of a solar system is no more complicated than the installation of a traditional heating system and a gas-condensing boiler. This would suggest that the need for multiple subcontractors may become redundant as the market matures. Even then, however, the issues of process management will need to be resolved if the production of low carbon housing is to be robust.

The design process

Despite the off-site nature of the superstructure, the design process was typical of a scheme procured through an architectural competition and administered using traditional methods involving architectural oversight and a construction contractor with a team of consultants, specialist subcontractors and suppliers. The retrospective interviews with the client, design and construction teams revealed disappointment among respondents with the superstructure construction delays. The disappointment was particularly acute given a general expectation among the respondents of faster construction times from off-site construction. Despite the disappointment there was broad agreement that design and construction team interactions and communications worked well and that detailed design information was adequate. A few comments suggested the need for more frequent site project meetings and there was agreement that the location of the architect's offices outside the region meant that the architect spent less time on site and was less able to address site problems as quickly as a locally based architect might have been able to do.

There was agreement that some of the problems and delays during construction could have been avoided with better communication, closer control of on-site processes, a more detailed analysis of potential issues at the design stage and a more rigorous process for the selection of key subcontractors based on an assessment of past performance. Another key design issue to emerge from the interviews was the need for the M&E consultant to become involved in the design process at an earlier stage than was the case at Elm Tree Mews. This resulted in design choices for fabric and services that, in some cases, were not as well integrated as they might have been. The questions over ventilation strategy are a case in point as the air tightness of the fabric is an important driver in ventilation design. As it turned out, the original air tightness target of 3 $m^3/(h.m^2)$ @ 50Pa was not carried through into detailed design and the measured air tightness did not conflict with the chosen ventilation approach. However, there was no evidence to suggest that the interaction was given significant consideration.

On the whole, the interview responses regarding the design process were related not to energy performance but to the general running of the project. However, the issues relating to energy and carbon performance lie in the lessons contained in the results of measurement and the feedback provided for future processes, in particular the verification of design assumptions and input into the model.

Fabric design

The post-construction measurement of fabric performance revealed a considerable gap between the design predictions of heat loss and the value established through whole house measurement. The research team's attempt to explain the gap, based on design and construction observations, demonstrated that, with the exception of the party wall bypass, a more rigorous approach to the calculation of fabric heat loss could have resulted in a closer match between measured and predicted values. The key performance characteristics included:

- the calculation of plain-wall and roof U-values, which did not take into account additional structural timber;

- the calculation of thermal bridging, which relied on a default value based on general assumptions with respect to construction details;

- a product-substitution decision that resulted in a 33 per cent increase in heat loss from windows and glazed doors;

- the existence of several thermal bypasses, most notably via the party wall cavity, but also through other cavities in the external envelope.

Thermal design of the timber frame

The calculation of heat losses from the timber-frame roof and wall sections can be estimated from standard calculation and numerical modelling methods that take account of both the timber-framing elements and the areas of insulation material. The problem at Elm Tree Mews was that, although available in the panel manufacturer's production drawings, the information on the number and distribution of timber elements was not used to calculate a more realistic heat loss estimate. It seems that the nominal U-value used at competition submission stage, which ignored the impact of structural timber, was not investigated or challenged later in the process. This problem is closely allied with the estimation of thermal bridging at the junctions between wall, roof and floors and around openings, none of which were calculated but simply assumed to match a default value.

The design issues are related to the processes involved in gathering the necessary information, the application of thermal calculation tools and the skills within the team to use them. It is very common in housing design for nominal U-values to be calculated by product manufacturers based on the use of their products. These values are used in design calculations and are rarely challenged or checked. In this respect the process at Elm Tree Mews was in line with standard practice. The approach to thermal bridging was also typical of housing design practice with most calculations applying the default value applied at Elm Tree Mews.[35]

In order to address the problems created by the use of nominal values, more effective use of existing calculation tools is needed. Also, more realistic values should be applied at scheme design stage, since it is at this point that the basic construction and structural form are established and will become increasingly difficult to change as design progresses. If the nominal U-values and thermal bridging at Elm Tree Mews had been challenged during detail design, it would have become apparent that the target standard would not have been met and significant changes to the construction would have been required.

Part of the difficulty in establishing thermal performance at Elm Tree Mews, and indeed many other schemes, is the diffuse nature of the responsibilities involved and the location of expertise. At Elm Tree Mews the frame manufacturer provided a nominal U-value for walls and roof, on which the design team relied. However, if challenged, the timber-frame manufacturer would have pointed out that since they had not designed the panels in detail at that stage, they could not have provided an accurate value nor would they expect to include thermal calculations as part of their design service. Similarly, they would not normally be expected to provide thermal bridging ψ-value calculations, even though most of the bridges were associated with the system they were designing. However, where there is a single manufacturer providing what is a fabric 'system', it is arguable that responsibility for the thermal design of the wall and roof system could have been incorporated into the manufacturer's brief.

Current industry practice places the responsibility for the structural design of the timber-frame panels with the manufacturer and it would be a natural extension of this role to include thermal design. Such an approach would put the responsibility in the hands of those who have the necessary information

and may lead to more thermally and structurally optimised designs as manufacturers would gain more experience and feedback on performance. This could add considerably to the potential offered by off-site construction.

Product substitution

The substitution of locally sourced windows for those originally specified is symptomatic of a more general problem of product substitution. Such substitutions occur quite regularly throughout the construction phase of many schemes. In the case of the windows at Elm Tree Mews, the reasons for the substitution were not unreasonable since, at the point of decision, it appeared to have cost advantages and could be considered more sustainable as it reduced environmental impact (minimisation of transport) and supported local small business. However, the substitution was made within a system that seemed to have weak modification controls. It is common for specifications to identify a specific product. However, this is qualified by allowing an alternative product to be used if it has the same or equivalent performance. The problem with this is that the process by which the substitution is to be checked against the performance requirement is often left unclear. Typically the decision is in the hands of a contractor's buying team who may ask for approval for the substitution but with little in the way of back-up data beyond the claims of the manufacturer that it is the equivalent of the product originally specified. Commonly, neither the buyer nor the person who gives approval is fully aware of all the details or the risks associated with any variation in the performance specification. Also, substitution decisions are often made under considerable time pressure, which can lead to simple mistakes. Indeed, the specification sheet for the substituted window clearly stated that the performance was based on mid-pane glazing U-value (as opposed to the required whole window U-value). The fact that this did not meet the required performance was not picked up in the decision process.

Ensuring performance equivalence is not a trivial problem and to expect detailed knowledge about the performance characteristics of every material and component in a building, even one as apparently simple as a house, is unrealistic. This means that, before a substitution is made, there should be processes in place that make clear the particular performance characteristics that are relevant, how these will be checked and by whom. The problem with specifications couched in terms of nominated product 'or its equivalent' is that the relevant performance characteristics embodied in the nominated product are not made explicit and there is considerable room for error and misunderstandings. In some cases, national certification schemes can assist the process. In the case of windows, the UK Window Energy Rating Scheme is available (BFRC, 2010) to ensure that performance characteristics are clear on a product-by-product basis. However, although the windows specified initially were certified, the locally made ones were not.

Thermal bypassing

Although the discovery of thermal bypass heat loss through party walls and similar construction cavities can be traced back to work undertaken in the late 1970s (Harrje, *et al.*, 1979; Harrje, *et al.*, 1985), it was not until detailed work during the Stamford Brook field trial (see Wingfield, *et al.*, 2008; Lowe, *et al.*, 2007) that it received more formal recognition in the UK. Its recognition in the 2010 edition of the Building Regulations in England and Wales (CLG, 2010) and in SAP 2009 (BRE, 2010) has reinforced its importance and is likely to ensure dissemination of the issue within the industry. Clearly, the designers of Elm Tree Mews would not have been aware of the problem. However, the effect proved to be significant and will need to be taken into account in future schemes.

The physical principles of the mechanism are reasonably clear but the precise effects are more difficult to determine in specific instances. Calculation and modelling tools are not yet available that would have enabled the effect of all the bypasses at Elm Tree Mews to be determined and, although there are generalised values provided with building regulation guidance for party wall cavities, these are extremely

rough estimates and do not cover other types of bypass. Given that calculation methods are not likely to be available for some time (if at all), it will be important for designers to develop a clear understanding of the principles involved and be able to recognise bypasses when they arise. In most cases it would be possible to avoid thermal bypassing by ensuring that the insulation layer and the air barrier are continuous and are either in direct contact or not separated by a cavity. This is reflected in the general guidance contained in the 2010 edition of the regulatory Approved Document L1A, which states:

> *The party wall is a particular case of the more general thermal bypass problem that occurs where the air barrier and the insulation layer are not contiguous and the cavity between them is subject to air movement. To avoid the consequent reduction in thermal performance, either the insulation layer should be contiguous with the air barrier at all points in the building envelope, or the space between them should be filled with solid material such as in a masonry wall.*
>
> (CLG, 2010)

This is sound guidance and if used with a good understanding of the principles involved should ensure the elimination of this type of heat loss mechanism.

Envelope complexity

Some of the difficulties in achieving robust thermal performance stemmed from the geometric complexity of the thermal envelope. Thermal bridging and thermal bypassing, in particular, were almost certainly increased, as was the effort involved in ensuring that details were constructed as designed. It is acknowledged that some of the complexity was driven by the aesthetic requirements of the development but it must also be understood that this brings with it an increased need to apply more design resources than would be necessary in instances where much less complexity is evident. In addition, there was little evidence to suggest that the impact of geometric complexity on thermal performance was considered during the design process, since little attention was given to the particular problems of air-barrier continuity at complex junctions, nor were calculations undertaken to provide information on thermal bridging. It is arguable that, had such issues been addressed at detailed design stage, an attempt would have been made to simplify the geometry without compromising the external aesthetic.

Services design

The technical difficulties of the initial design and installation of the heating and hot water systems at Elm Tree Mews are documented in Chapters 3 and 4. To some extent the problems revolve around the novel nature of the system and, with hindsight, the enterprise was always likely to carry significant risks. However, the experience has highlighted a number of problems that are of a systemic nature. These are set out in the sections below.

Design data, tools and guidance

Although assumptions on heat pump performance are contained within SAP, there is little, if any, hard data on system interactions and their impact on performance. The strategic decision to use a communal heat pump was based on calculations done using the generalised assumptions in SAP coupled with a belief, based on manufacturer's claims for the CoP of the heat pump, that the SAP assumptions could prove to be conservative. In the event, the assumptions turned out to be a significant overestimate.

In the case of the heat pump, once the strategic decision had been made to use a communal system, the detailed design process had to rely on the application of general engineering principles, such as those found in standard services design guidance (for example CIBSE, 2005) and the garnering of

judgements from the manufacturer and the heat pump subcontractor. To what extent the judgements and advice provided were based on as-installed performance data is not clear, but there is very little detailed information in the public domain that a services engineer could apply. In order for the detailed design to be able to consider the likely performance of a system as a whole, it would be necessary to have a modelling capability, supported by operational data that was able to predict the performance impacts of all components working in concert under a particular control and usage regime. Although modelling capacity exists to evaluate the 'bench' performance of individual parts of the system, as far as the research team are aware, modelling tools to analyse the performance of whole systems and the likely effect of system interactions on overall efficiency are not readily available.

Control complexity

The performance observations and issues relating to system controls would suggest that the design of space and water heating was overambitious. Water heating, in particular, was complex since it consisted of three different heat inputs at different temperatures and, in the case of the solar system, was dependent on the weather. This provided considerable difficulty in designing effective control. The problem of legionella, which necessitated a weekly pasteurisation cycle, provided additional complexity. The consequences of such a complex design included reduced amenity for residents, suboptimal operation of the heat pump, increased electrical consumption of the pasteurisation shunt pump and the need for the Housing Trust to monitor bacteria levels. The results of monitoring suggest that, in the absence of tried and tested control solutions for such complex arrangements, high levels of complexity carry a high risk of unintended consequences.

Systems design and performance diagnostics

The carbon performance at Elm Tree Mews was highly dependent on the performance of the novel services solutions that were designed. However, as was observed in Chapters 3 and 4, many of the operational difficulties were only identified because of the monitoring data provided by the research project. The kinked pipe work in the solar systems or the mixing up of flow and return pipes was largely undetectable, at least initially. As long as heat is provided, occupants have no way of knowing whether the system is delivering the performance promised.

The systems installed, as in almost all domestic systems, had no self-diagnostic capacity or performance monitoring built in. In principle, the systems could have been designed to incorporate information on their performance and whether reasonable levels were being maintained. Of course, to do so in a bespoke manner would have been prohibitively expensive. However, in the long term, if low carbon housing is not to depart from its initial performance level, there will need to be mechanisms by which warning signals are available so that initial performance can be checked and any long-term drift in performance can be corrected through appropriate servicing and maintenance.

The construction process

The construction process was subject to delays and technical problems, particularly in relation to the erection of the timber frame. Although the technical problems did not impact significantly on thermal performance, some issues arose during construction of the party walls. The erection of some of the party wall panels the wrong way around was indicative of the need for closer control both in the factory and on site. That it was possible to get panels in the wrong place and the wrong way around is a matter for the design of the panels, the labelling system used to identify location and orientation, and erection instructions. Indeed, it would have been possible to design junctions in such a way that there was only one way the panels could have been erected. The structural problems caused by panel misalignment were resolved

satisfactorily on site but the significance of this and other problems lies in the understanding it provides about the level of process detail needed both in the design office and on site to ensure that mistakes are eliminated.

Despite general construction problems, the underperformance of the fabric was largely due to the assumptions made in the design process rather than the construction team not constructing according to the design. The only aspects of fabric performance that could be associated with construction actions was the fitting of insulation in areas such as the bay-window roofs and the fitting of edge sealing to the party wall cavities. In the case of the roof insulation, the loose fitting allowed air movement to degrade the insulation value and, in the case of the cavity edge sealing, the resulting air movement within the party wall cavities enabled the operation of a party wall thermal bypass. The general lesson in these instances is the need for more understanding both in design and among site operatives of the importance of eliminating air movement around insulation and through construction cavities.

Sequencing of installation

Some issues arose with respect to construction sequencing that led to problems with the fitting of the communal heat main. Sequencing is a common cause of difficulties in all aspects of construction. In the case of fabric performance it is an important factor in maintaining the thermal integrity of insulation, particularly at difficult junctions, and of fitting services through insulation layers and the air barrier. Since the envelope was made up of off-site manufactured panels this was less of a problem than on other, more traditional, schemes.

The specific sequencing problem at Elm Tree Mews was the fact that the heat main was installed at a late stage when the ground floor and superstructure were largely complete. It would have been much easier to lay the pipe work after the completion of the foundations and before the construction of the beam and block floor. The obstruction formed by the walls and floor caused significant difficulties as the pipe had to be fed through holes in the foundation wall and under the floor to the entry point in the middle of each dwelling (see Figure 36). As the pre-insulated pipe is relatively inflexible (minimum bend radius 0.7m), the construction operatives found it impossible to feed the pipe under the floor without stripping back the pre-fitted pipe insulation. In some cases the outer protective sheath of the pipe was removed, which would allow water ingress into the insulation and the eventual deterioration of its insulating properties. This would have the effect of increasing the heat loss from the main and degrading system performance.

Services installation issues in relation to solar water systems have already been described in the context of the procurement process. The fact that only one dwelling did not experience installation problems is symptomatic of an approach to services installation that was not well controlled. Nails through pipe work and kinked pipe work are relatively common in all pipe-work installations. The lack of designed services runs in ducts with full access for maintenance and repair has been complained about for many years among maintenance personnel, yet dwellings are still designed and constructed without a thought to this problem. Many of the problems with the solar installation could have been avoided if more thought had been applied to the problem of services routing as well as labelling and the use of a more sophisticated pipe-work system.

Commissioning processes

The commissioning processes adopted for both water and space heating services were not robust enough to identify many of the performance and installation issues discovered during monitoring. It would seem that commissioning sought to go no further than establishing if the equipment (mainly pumps) ran when switched on rather than operated to the level of performance that was intended. In the case of the solar systems, the kinked pipe work could have been discovered with a simple flow test carried out prior to making connections and/or at commissioning. Other difficulties, such as the frost protection setting,

Figure 36: Installation of district heating pipe work

District heating pipe being fed under ground floor of dwelling through hole in foundation wall

Insulation layer stripped away to enable pipes to be drawn through the floor

Pipe work below the floor showing outer protective sheath and insulation stripped away to enable the pipe to be bent

could have been minimised by the use of a commissioning checklist. In no case was there any testing of performance at the point of commissioning. We have noted already that systems could be designed that would monitor their own performance and provide diagnostic information to occupants and a servicing engineer. The incorporation of such devices would also aid a commissioning process, which could include a series of simulation tests designed to establish a likely performance range under different conditions of use. A more rigorous approach is likely to result in increased commissioning costs but may also lead to a reduction in call-back costs and would reduce disruption to residents and landlords alike.

The resident experience

In Chapter 4 we attempted to understand physical performance characteristics and to relate them to the experience of residents. This was deliberate since, together, the dwelling and its residents constitute a system, which in an ideal world would enable people to live their chosen lifestyle while enabling energy consumption and carbon emissions to be minimised. In this section we attempt to draw out the general implications of the resident experience for the design and construction of low carbon housing.

Predicting interactions between people and their homes is difficult, and achieving the ideal arrangement equally problematic. However, the process of understanding the interactions is often not given the same priority as other features, nor is it common to seek resident feedback at the level of detail required to understand the interactions involved, or to analyse the different lifestyles that a dwelling may need to support. Elm Tree Mews provided yet another example of a dwelling design that in some respects was not in complete harmony with the twin objectives of providing for resident comfort and amenity and reducing carbon.

Perhaps what is missing is a set of practical tools that can be used at design stage and provide an opportunity to simulate how a design might be used. To a large extent models of use are informal and hidden inside the heads of designers and are not amenable to analysis because they are not explicit. Without some formal way of describing the way a dwelling is supposed to operate under different conditions and lifestyles, it is difficult to use what feedback may be available since there is no frame of reference relating to design expectations or intentions. User-based design has been a recurring theme in the design theory literature for a number of decades but little practical guidance is available for the designers of dwellings. Post-occupancy evaluation in the non-dwelling sector is being used increasingly and has been applied to dwellings, but often the feedback provided by such studies is broad and does not deliver practical guidance. As a consequence it does not find its way into dwelling design as a matter of routine.

Continuous improvement: the microfeedback loop

The principle of continuous improvement is enshrined in the mission statements of many public and private sector organisations. However, in order for such a principle to be realised within an organisation there must be mechanisms that enable learning from one set of experiences to be fed back into the organisation so that future processes are improved. Indeed, one of the objectives of the Elm Tree Mews scheme was to inform the design and development of a much larger, 540-dwelling, JRHT scheme on the eastern edge of York. The emerging results from post-construction testing at Elm Tree Mews gave significant impetus to this role, so much so, that the Housing Trust took the decision to design and construct two prototype dwelling types (The Temple Avenue Project – TAP) that would provide an opportunity to extend the learning process in a practical way.

The post-construction results from Elm Tree Mews were available in the late spring of 2008 and the research team was asked to provide a report on performance and other issues that should be fed back to the design and construction team. The report that emerged (Wingfield, *et al.*, 2008) was informed also by the research team's work on the Stamford Brook field trial, which had just been completed (Wingfield, *et al.*, 2008). Nine recommendations emerged from the report dealing with matters of low carbon design, construction technology, and design and construction process. The report was presented to the prototype development team who sought to adopt and act upon what had been learned.

In addition to feeding back to the designer and constructor of the Temple Avenue prototypes, the research team was engaged to work with the designer and contractor so that the feedback could be reinforced constantly and woven into the fabric of the prototype project. The prototypes were subjected to the same level of post-construction fabric performance testing as at Elm Tree Mews. Although the feedback and its impact have yet to be explored with the design and construction team, post-construction performance measurements are encouraging (Miles-Shenton, *et al.*, 2010). Each of the prototypes was

identical in form and layout (both were detached) but adopted different construction technologies. One was externally insulated thin joint masonry and one used a structural insulated timber panel system (SIPS).[36] Figure 37 sets out the percentage discrepancy between designed and measured heat loss for the TAP dwellings and Elm Tree Mews. These data indicate a much closer agreement in the TAP dwellings (10–15 per cent) than was achieved at Elm Tree Mews (54 per cent or 38 per cent depending on whether the party wall loss is included).

The observations, based on close contact with the design and construction team, would suggest improvement of the following processes:

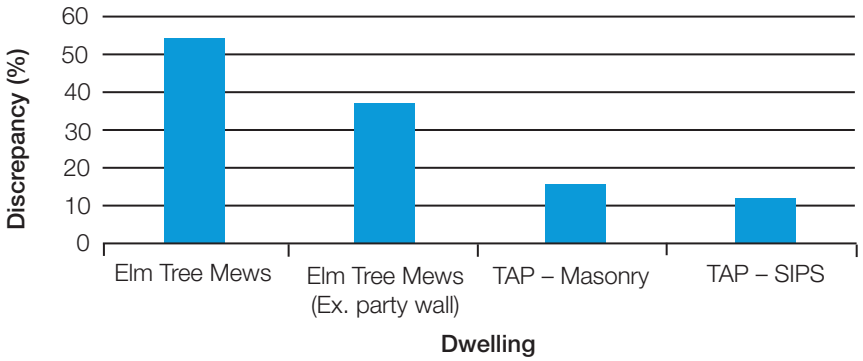
- The designer gave priority to providing accurate estimates of fabric heat loss, even to the point of insisting, in the face of some reluctance, that the SIPS manufacturer provide details of the amount of timber that penetrates the insulation layer. Considerable effort was put into air-barrier design, even to the point of building physical models of geometrically complex details. Also, the designer increased the detailed design capability of the team so that they could undertake detailed thermal analysis, particularly in relation to thermal bridging. The modelling skills developed by the design team are relatively unusual outside the specialist modelling community.

- The contractor worked very closely with the design and research teams to ensure that the site staff understood what was required and put in place processes that would not only improve awareness of the key requirements but also sequences of construction that would aid effective thermal construction and inspection.

Although it could be argued that some design and construction issues remain at Temple Avenue, they are less marked than at Elm Tree Mews. Continuous improvement is a never-ending process and it is hoped that the learning gained from the Temple Avenue project, which is still being captured by the research team and other project members, will be fed back into any future developments that are undertaken by the Housing Trust and by the design and construction organisations involved. In addition, the results of the post-construction testing at Temple Avenue will provide valuable material for improvements in the material and component supply chain, improvements that will enable the achievements of robust thermal envelope systems.

The potential for creating feedback loops and enabling them to contribute to continuous improvement within organisations is demonstrated by the JRHT experience of the Elm Tree Mews and Temple Avenue projects. However, the development of positive attitudes to what is often seen as failure is crucial to wider success. The construction industry as a whole is prone to blame and to legal claims and counterclaims. To some degree this is an inevitable reflection of the nature of the responsibilities involved and the potential scale of the financial losses that could be incurred. However, ways must be found to keep such issues under control, for without an open approach and willingness to learn from both success and failure, progress to genuine zero carbon housing will be patchy and slow.

Figure 37: Comparison between heat loss discrepancy at Elm Tree Mews and Temple Avenue dwellings

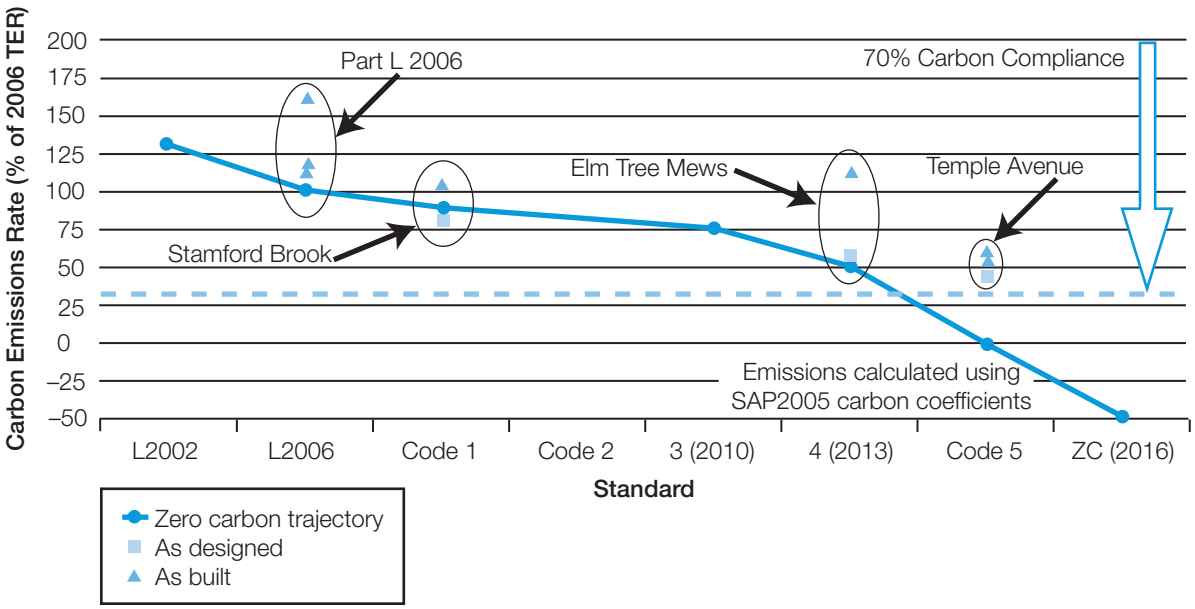


6 Issues for government, housing providers and other stakeholders

The energy and carbon performance achieved at Elm Tree Mews was well below expectations. When coupled with evidence of underperformance from other studies, a growing picture is emerging of a significant gap between what is predicted at the design stage and what is achieved in practice. It was noted in Chapter 1 that national unease about the extent of achievement of regulatory standards is increasing. Given the ambitious carbon reduction targets that have been set in the UK and, increasingly, in other parts of the world, it is important that as much understanding as possible is extracted from detailed studies such as Elm Tree Mews and, latterly, the Temple Avenue project.

Figure 38 places the performance at Elm Tree Mews in the context of the national policy objective and compares the performance of other schemes that have been measured by the Leeds Met research team (Stamford Brook and various Part L 2006 schemes) as well as Elm Tree Mews and Temple Avenue.[37] The zero carbon trajectory in Figure 38 is based on the carbon performance levels contained in the Code for Sustainable Homes (CLG, 2008a), the anticipated regulatory trajectory (2010, 2013 and 2016) and the minimum carbon compliance level under the definition of zero carbon. It is clear from the figure that the gap between as-designed and as-constructed performance can be significant. The design of the Elm Tree Mews scheme would give a performance level close to that which would satisfy the carbon compliance standard envisaged under the definition of zero carbon. However, its measured performance was closer to the 2006 regulatory standard, with estimated carbon emissions around 75 per cent higher than that intended at the design stage. The benefit of feedback from Elm Tree Mews is evident in the much smaller gap that is apparent in the Temple Avenue scheme.

Figure 38: As-designed and as-constructed performance of Elm Tree Mews in the context of other studies and the regulatory trajectory to zero carbon



Underperformance in house building

One interpretation of the results from Elm Tree Mews could be that, as a stand-alone case study, it does not provide evidence of general underperformance in mainstream house building. Although the data shown in Figure 38 goes some way towards demonstrating that the results of Elm Tree Mews are part of a general picture of underperformance in carbon terms, it is worth exploring the evidence of underperformance in more detail.

Defects in traditional housing

Quality of construction in general has been a recurring theme in a number of reports on the construction industry going back to the 1960s (Banwell, 1964). However, the first detailed study of defects in traditional housing was undertaken in the late 1970s and early 1980s (Bonshor and Harrison, 1982a; Bonshor and Harrison, 1982b) with a follow-up study undertaken in the early 1990s (Harrison, 1993). These studies, conducted between 20 and 30 years ago, produced a large catalogue of significant defects. What is more, the second study reported very little improvement over the ten years between the studies. More recent work focusing on energy efficiency and the application of the 2002 Part L thermal robust details (Bell, *et al.*, 2005) suggests that nothing much seems to have changed since the early 1990s, with a similar range of defects observed in such things as the fitting of insulation and the construction of details.

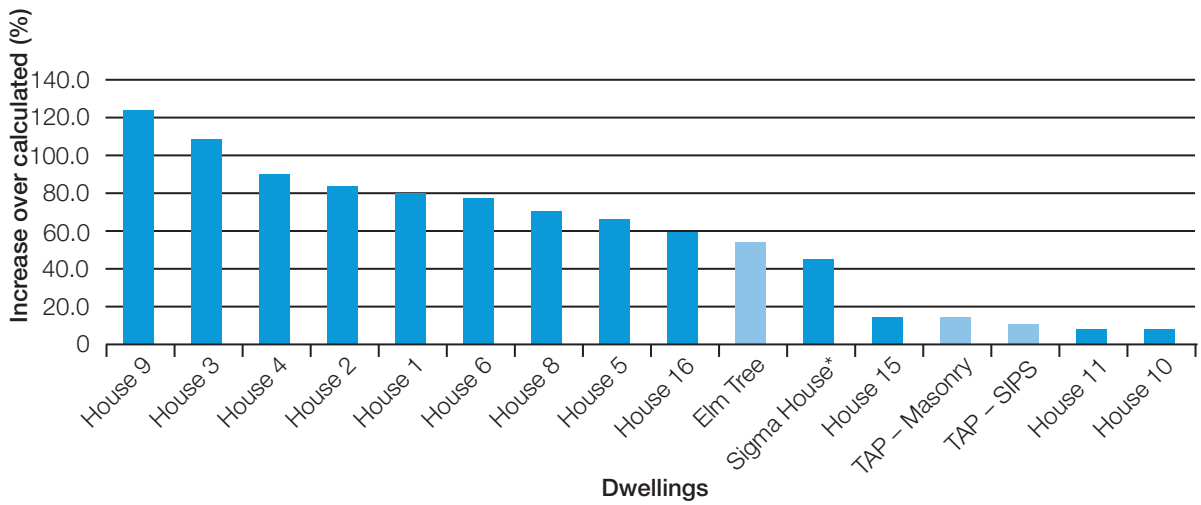
Fabric heat loss performance

Although there is a need for more data on whole house heat loss, the body of evidence for a large performance gap is increasing all the time. Figure 39 shows the percentage discrepancy between the designed heat loss value and that measured for 16 new dwellings (including Elm Tree Mews and TAP), which were carried out between the winters of 2005/6 and 2009/10. The results from Elm Tree Mews and the Temple Avenue project are highlighted. The absolute discrepancy in heat loss can be seen in Figure 40, which shows the measured and predicted heat loss for the test houses presented in the same order as in Figure 39. All tests, with the exception of the Sigma House, were carried out by the Buildings and Sustainability group at Leeds Metropolitan University. The results are for a mix of house types and sizes, mostly of two and three storeys, with the exception of the Sigma House, which is a four-storey design. Two of the dwellings were detached houses, with the remainder being a mixture of semi-detached, mid- and end-terrace houses.

Only four out of the sixteen houses demonstrate even a reasonably close match at around +10 per cent to +15 per cent. None of the dwellings had a measured value that was less than the predicted value. Although the sample could not be described as being representative of all dwelling production, it is perhaps surprising that so few are even remotely close to the predicted value and none are lower than predicted. This is of particular concern when one considers the fact that over half the cases relate to schemes that had a particular focus on improved energy performance.

Further evidence of underperformance of dwelling fabric is provided by a number of studies that measured in situ envelope heat flux, from which indicative U-values were derived. The evidence available in the UK is derived from work by Siviour (1994), Doran (2000), and measurements made during coheating tests undertaken by the Leeds Metropolitan University team at Elm Tree Mews and elsewhere. In broad terms, all studies demonstrate that there are large differences between calculated and measured values. In many cases measured heat losses can be over 50 per cent higher than calculated and at the extreme over 200 per cent higher. There were relatively few cases in which no discrepancy occurred or where measured values were better than calculated. Laboratory work carried out in Belgium on cavity masonry walls, much of which is consolidated in Hens, *et al.* (2007) has shown that heat loss from walls can be significantly in excess of that predicted as a result of defects in the installation of the cavity wall insulation.

Figure 39: Predicted versus measured whole house heat loss – percentage discrepancy in 16 new dwellings[38]



* Sigma House was tested by Oxford Brookes University.

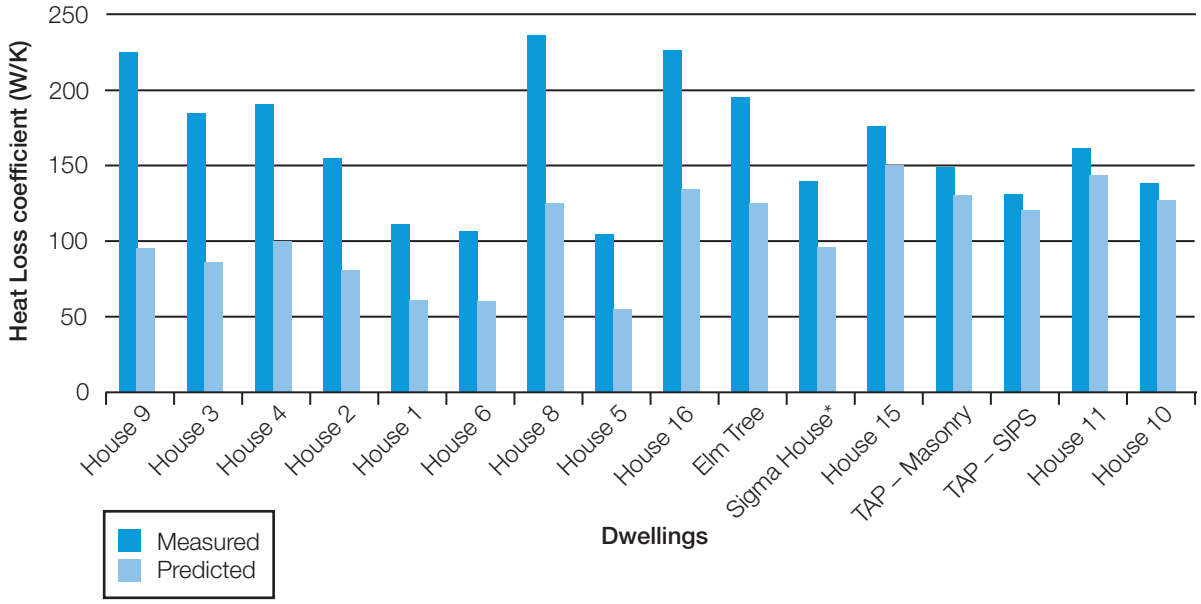
Heating and hot water services

As with fabric performance, the underperformance of the heat pump installation at Elm Tree Mews would appear to be part of a much broader canvas of the underperformance of heating systems, hot water systems and other services such as ventilation systems. Emerging evidence from measurements of some 27 conventional gas-condensing boiler installations is demonstrating that boiler efficiencies, as-installed and in use, are likely to be some five percentage points below their SEDBUK rating (Carbon Trust, 2007). Findings from measurements of condensing gas boiler performance carried out for the Carbon Trust's research into micro-CHP indicate that electricity consumption for controls, fans and pumps can be higher than expected by a factor of around two. This has considerable implications for standards based on carbon emissions, since boilers of the same nominal thermal efficiency could emit significantly different amounts of carbon depending upon the parasitic electricity consumption (Carbon Trust, 2007). The evidence from Stamford Brook provides a similar picture with estimated boiler efficiencies of the order of 86 per cent compared with a SEDBUK rating of 91 per cent in the small number of cases monitored. Some corroboration of these results has emerged from more recent work done on behalf of the Energy Saving Trust (Orr, *et al.*, 2009), which indicated efficiency values for the ten regular boilers measured that were around five percentage points lower than their rated SEDBUK value. The range of the discrepancy was from about two points to nine points.

In addition to boiler performance, it is important to remember that fuel consumption will be influenced by whole system effects that take into account the interaction of all the various system components. This would be influenced by factors such as standing losses, distribution losses, cycling effects and start-up inefficiencies. The overall system efficiency will always tend to be lower than the nominal efficiency of the main heating source on its own. This is illustrated in Figure 41 taken from the Stamford Brook report (Wingfield, *et al.*, 2008). In this graph the whole system efficiency in dwelling C dips as low as 55 per cent during the summer months, whereas the boiler efficiency on its own is around 85 per cent. The system efficiency was improved through user advice but even then summer efficiencies for the whole system did not rise above 65 per cent. In dwelling C some of the cause of the low system efficiency was related to long and uninsulated primary flow and return pipe work between the boiler and hot water storage vessel. Even though the drop in efficiency was not as marked in dwelling K where the primary pipe work was not as long, the system efficiency was still only between 70 per cent and 75 per cent. The SAP model does not take into account the effects of system efficiencies.

The findings from other studies, particularly in relation to systems' impacts, echo the sort of systems issues identified at Elm Tree Mews. However, with conventional gas boiler systems, the effect of lower

Figure 40: Predicted versus measured whole house heat loss in 16 new dwellings



* Sigma House was tested by Oxford Brookes University.

system efficiencies on overall performance is likely to be less marked than the situation at Elm Tree Mews. A system CoP of three or better for the heat pump at Elm Tree Mews was crucial to achieving the designed carbon emission rate, since without it carbon emissions would have been worse than those that could have been achieved with a conventional gas boiler. The overall performance of the dwelling would have been closer to that of the 2006 Building Regulations than that of the advanced standard required by the project brief.

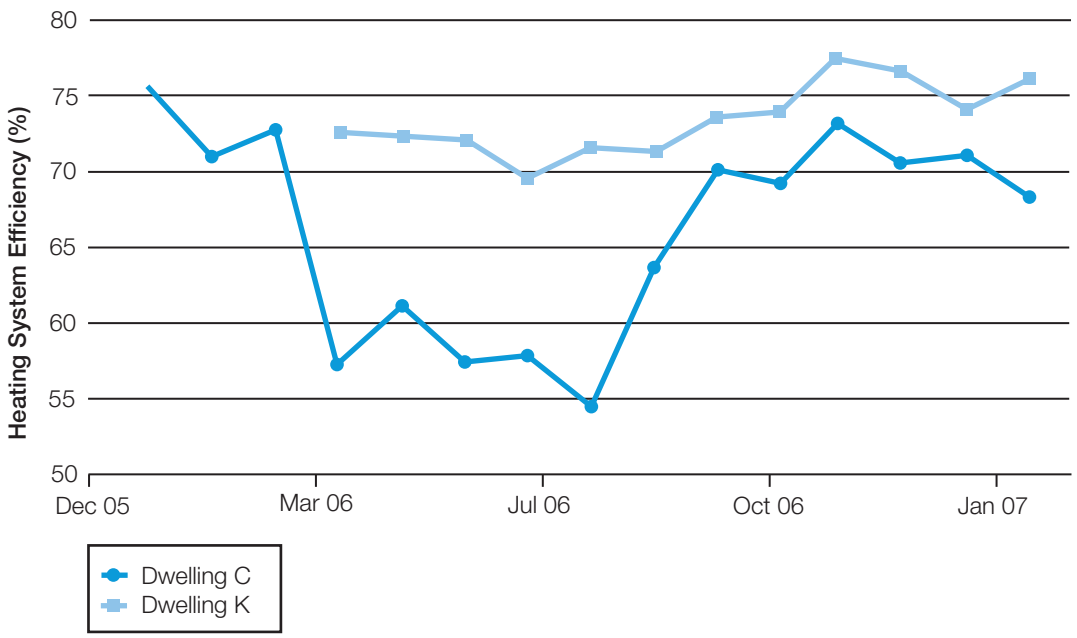
The house-building industry and its environment

The findings from Elm Tree Mews and elsewhere have considerable implications for the whole of the house-building industry, its supply chain and the supporting environment, including such things as: education and training, research and development, industry cultures and government policy. Many of the performance issues observed are matters of system and process rather than simple mistakes or oversights. The implications of Elm Tree Mews for design and construction processes have been discussed in Chapter 5. The wider implications for the industry and its supporting infrastructure are drawn out below.

Developer policies

At the very early stage of any housing development, the setting of performance targets and the general approaches adopted in terms of design and procurement are fundamental and these will be determined, in most cases, by the general policies that the developer adopts as part of the business model. It makes little difference whether developers adopt traditional client-designer-contractor arrangements, as at Elm Tree Mews, or a commercial speculative development typical of the private sector. In all cases requirements and targets are set as a matter of developer policy, but they are set within a system of expectations about the extent to which the requirements can and will be met. The evidence from Elm Tree Mews and elsewhere would suggest that as far as energy and carbon emissions are concerned, there is a tacit belief that what is modelled in SAP is achieved and that there is therefore no need to check performance. The emerging evidence on realised performance, coupled with increasingly stringent performance requirements, means that such a belief can no longer be sustained.

Figure 41: Monthly heating system efficiencies – Stamford Brook field trial (Wingfield, *et al.*, 2008)



The approach to checking energy and carbon performance is not manifest in other areas such as appearance and quality of finish. The reason is obvious. Appearance can be assessed by visual inspection and compared with design images, well-understood visual standards and normative notions of what looks 'good'. Indeed, the overall satisfaction with the completed scheme, as expressed in the interviews with the Elm Tree Mews design and construction team, was based mainly on visual rather than energy performance. This one-dimensional approach to performance tends to dominate and all other performance characteristics, including resident considerations, as well as energy measurement, are relegated to second place. There is a need, as never before, to ensure that realised energy and carbon performance is given a higher priority as a matter of development policy and that early decision-making processes need to ask some fundamental questions about how performance would be demonstrated and what processes should be put in place to ensure that design expectations are realised in practice.

The challenge for the development industry and its clients is to begin to ask the important questions about performance control and verification and to change the way it thinks about the design and construction processes. Lowe, *et al.* (2003) have likened the required change to the construction industry's equivalent of paradigm shift (Kuhn, 1962). This concept is useful because it captures the fact that, in order to happen at all, the new paradigm must become the norm. However, during any paradigm shift there is an unsettled period in which the old and the new vie for supremacy. In such a period, those more forward-thinking companies who adopt the new paradigm, in an effort to improve energy performance, may suffer increased costs in the short term but gain no competitive advantage because the underperformance of others is not apparent. In a very competitive housing development market such companies would find it difficult to sustain a viable business model, whether in the public or the private sector. It is incumbent on the whole housing development industry to move together in the task of retooling their approaches and processes, and ensure that there is a level playing field so that there are no disincentives or barriers to change. However, unless the commercial imperatives relating to demands from house buyers and tenants become significant, the necessary paradigm shift is unlikely without fundamental change in regulation and its enforcement.

The supply chain

The supply chain, and its supporting infrastructure, consists of the traditional supply of materials and components, supply of skilled labour (at all levels during the process), and in areas, such as general

construction education, ongoing technical advice systems (such as that from the Energy Saving Trust), professional bodies and building control. It is not possible to explore all the different elements in detail but some of the more immediate areas are discussed in the sections below.

The material and component supply chain

To a large extent, house design in the UK is driven by the type and availability of components and materials from construction product manufacturers and materials supply industries. In order to sell their products in the face of stiff competition, the supply chain will tend to present product performance in the best possible light. However, as demonstrated at Elm Tree Mews, product performance can be different when installed. It is arguable that there is an urgent need for closer and more effective working relationships between house builders and their supply chain so that there is better understanding of performance in a particular design and construction context. Such a relationship would involve the supply chain taking its share of responsibility for ensuring that their products are applied appropriately and that designers, developers and constructors have more realistic estimates of as-constructed performance.

In the case of Elm Tree Mews, the role of the off-site panel system manufacturer was important in ensuring that the required thermal envelope performance was achieved. Had responsibility for the thermal performance of the closed panel system been placed with the manufacturer, they probably would have had to take more interest in both design and construction. Indeed, a full and detailed calculation of heat loss during the design of the various different timber-frame panels would have uncovered the difficulties of coping with the additional structural timber. Since the target U-value (0.18 W/m^2K) would have been difficult to achieve with the design as used, important modifications could have been made at the design stage. Of course, if the timber-frame manufacturers were expected routinely to take responsibility for as-constructed thermal as well as structural performance of their systems, a vastly improved thermal design would have already been tried and tested. The principle holds for both fabric and services. A solar thermal system manufacturer who was responsible for as-installed performance would have been driven to improved commissioning processes and performance diagnostics.

It is accepted that, in the current climate, where underperformance is largely undetected, there are no commercial drivers for either developers or the supply chain to improve as-constructed performance or even to acknowledge that there is a problem. Any supplier who downgrades product performance claims to suit a particular context would not be able to compete with others who did not. Equally, suppliers of components using additional material to offset expected underperformance could reduce the competitiveness of their products when compared with other suppliers. However, it would also be expected that in a scenario where as-installed thermal performance was routinely checked and measured, this would lead directly to new innovations and improved products in the longer term.

The labour supply chain

The supply of labour with the requisite skills is a difficult and long-term problem. Although a great deal of emphasis is likely to be placed on education and training, which is discussed below, the structure of the labour supply chain itself will need to adapt to the demands that will be placed on it by the requirement for zero carbon housing. It is worth reflecting also that many of the labour supply issues that relate to new house building will have a parallel in the housing refurbishment market, where issues of control are likely to be more acute than in new building.

To some extent, the existing approach to skills in energy efficient housing has been to see them as specialist and not something that needs to be built into the skill sets of everyone in the team. While it is acknowledged that proof of specialist competency will be important for some purposes, there are many aspects that do not need to be separated from mainstream processes of design and construction. The needs of energy efficient design and construction are all-pervasive and to seek to specialise the

labour supply chain so that energy efficiency becomes the responsibility of a small number of 'experts' risks significant inefficiencies and a tendency for others to avoid responsibility rather than to embrace the requirements. During the Stamford Brook field trial (Wingfield, *et al.*, 2008) attempts were made to enable the site managers to undertake their own air leakage tests during production. The developers invested in the equipment but it went largely unused and pressure testing was left to the research team as a specialist activity. This was unfortunate because the opportunities for learning and development that could have been taken were lost. Also, it would have enabled in-production testing that could have picked up problems at an early stage and improved air tightness overall.

The issues of skill supply are particularly relevant for building professional bodies as well as professionals themselves. In rethinking professional roles and skill sets it will be necessary to understand the extent of responsibilities and the level of knowledge and skill required in each area. The tendency to date has been to see energy performance skills in terms of energy assessment for the purposes of producing Energy Performance Certificates (EPC), SAP calculations for new dwellings and Display Energy Certificates (DEC). Such assessments are now required under legislation, which was driven by the requirements of the European Performance of Buildings Directive (EPBD, 2003). In order to meet the legislative requirements training courses and national qualification structures were put in place (see Asset Skills, 2007). The impact of this legislation runs the risk of separating energy performance from other matters of design and construction. The danger in this approach is the growth of a new profession that is not fully engaged in design and construction. In a review of the operation of the Building Regulations Part L 2006 (Bell, *et al.*, 2010b), it was clear that, in many cases, the energy calculations were done outside the design process and there was little integration or feedback.

There were few instances of the regulatory modelling tools (SAP and SBEM) being integrated into the design process and used as design tools. Assessment of carbon emissions is normally given to assessors who are physically and contractually separated from construction and whose only role is to produce a statement which can be used to show compliance with regulation (Bell, *et al.*, 2010b, p. 9).

The problem with what would appear to be a developing trend in which issues of energy and carbon performance are seen as a specialist profession, divorced from the mainstream of design and construction, is that responsibilities become fragmented and design and construction less integrated. All members of the team need some understanding and skill related to their role since they all contribute. At Elm Tree Mews the final choice of the window was made or, at least, implemented by the contractor's buyer. This is not unusual since in private sector developments the buying departments are constantly looking to source materials and components based on price as well as performance. Without sufficient knowledge about energy performance at the point of decision and/or an effective modification approvals process the sort of product-substitution error that was made at Elm Tree Mews will continue.

Education and training

There is little doubt that the supporting skill base for energy efficient design and construction is weak, despite the existence, for the last 20 years, of a government-funded housing efficiency best practice programme, which has published a great deal of free guidance. The discussion of the approach to labour skills above is, in part, a symptom of this. Ways need to be found to improve skills at all levels, from the formal education system to the training and experiential learning that goes on within all parts of the industry. This will require not only stronger programmes from education providers but also will need to be linked to parallel work in the development of construction processes since, as with many aspects, it will be process improvement that will drive training and skills needs.

Education, training and skills development needs to take place across a broad front. However, the problem is likely to be one of demand rather than supply. The industry as a whole as well as government are only just beginning to grasp the fact that there is a need for fundamental change. The nature of that

change and the regulatory structures to support it are not well worked out. Given the general lack of awareness of the problem and no significant regulatory driver, few within the industry will clamour for the training that will be required. However, where the imperatives for change exist, they will drive the learning process. A good example is provided by the experience of the Joseph Rowntree Housing Trust in using the feedback from Elm Tree Mews to inform the processes for the design and construction of the prototype dwellings at Temple Avenue. In this case, the challenge to the designers and constructors was to deliver dwellings that, when tested, would perform as predicted. What is more, the particular lessons from Elm Tree Mews in relation to fabric design spawned considerable learning activity within the Temple Avenue design team. With assistance from the researchers, one member of the designer's team was able to learn how to calculate thermal bridging using numerical modelling software and others undertook similar skill development in the area of air tightness.

The learning that took place within the design team for Temple Avenue was considerable and of greater value than any training course would have been because it was continually driven by the requirements of the project. It is hoped that the skills will be reinforced and diffused throughout the organisation, but without a continuing requirement, and funding, to undertake the same level of design precision on other projects, such diffusion is unlikely to take place. What is more, if there is no continuing requirement the skills may well be lost when people leave or become rusty for want of practice.

Government policy, regulation and process improvement

The role of government is to establish a system of regulation and policy that provides a framework in which the house-building industry delivers the required level of performance. To date that framework has not been constructed in such a way as to objectively demonstrate that standards have been realised. The evidence from Elm Tree Mews and elsewhere suggests that standards are unlikely to be met in a significant number of cases. This is echoed by a lack of confidence among the building control community and others in the industry that theoretical performance is achieved in practice (Bell, *et al.*, 2010b). Of course, even if there was no evidence of underperformance, no rational government could leave the achievement of zero carbon homes to chance. Even a cursory inspection of the current system of building control would conclude that it is not in a position to verify performance in an objective manner since it is based on inspection of plans, infrequent site inspections and little (if any) objective measurement.

Regulation and building control

The current approach to building control, in which the Building Control Body tends to operate informally as part of the developer's quality control system, cannot continue. Despite the recent review of building control (CLG, 2009e), which modifies but leaves the existing system largely unchanged, it is time to rethink radically how the system works. In the long term, the industry (developers, designers, consultants, contractors and the supply chain) must take responsibility for compliance with regulation and provide sufficient evidence to an auditing body. Failure to comply, as evidenced by robust testing, must carry a sufficiently high commercial and legal risk as to be unthinkable. In establishing such a framework, a level playing field could be created such that all developers have to put in place the necessary performance controls or risk going out of business. This would be in sharp contrast to the current position where any conscientious developer who incurred the costs of increased performance control would be at a disadvantage compared with competitors who did not, because it is unlikely that anyone would know the difference.

Under a redesigned building control system developers would be required to demonstrate that they:

- have robust design and construction processes in place and that those processes are operating;

- have an effective measurement and testing regime in place and that the test results are independently verified;

- are able to provide a database of the performance achieved for each cohort of dwelling production; and

- provide evidence of review and constant evaluation of performance.

It is inevitable that, in such a system, skills within building control would have to change, at least for some sections. As far as energy and carbon performance is concerned, rather than focusing on the direct inspection of construction, building control would need to develop skills as auditors of process and quality control systems and evaluators of performance data. Clearly, such a radical change would have consequences for other parts of the regulations but it is arguable that a similar approach to other parts would benefit from the culture changes that would ensue from tackling the issues involved in improving energy and carbon performance.

In the consideration of regulatory revision for 2010, the Government has already begun to consider the sort of change that could be required. In the 2009 consultation document on proposed changes to Part L of the Building Regulations for 2010 (CLG, 2009b), three components of a revised system were discussed based on earlier work by an industry advisory group consulted as part of the review (Bell, 2008).[39] These have been further developed by Topic Work Group 4 (Bell, *et al.*, 2010a) of the Zero Carbon Hub (ZCH) Carbon Compliance Tool Policy Assumptions Task Group, which reported to government in the summer of 2010 (ZCH, 2010). The three elements under discussion are as follows:

- **Tolerance/confidence-based design** Such an approach would make allowance for known variability in performance, given a particular level of performance control. In some cases this could involve adding factors of safety or 'confidence factors' to theoretical predictions producing designs that are reasonably conservative. The use of confidence factors that reflect the risks of underperformance would provide an incentive for the industry to improve. Those developers that could demonstrate that their processes produced dwellings that performed as predicted would benefit by having no or relatively small confidence factors applied.

- **Performance control systems** This would seek to develop a rigorous approach to both design and construction that ensured accuracy of design calculations, effective information provision and communication and well-controlled construction processes. Such systems would include in-production testing at points when errors can be detected and rectified.

- **Post-construction measurement and verification** Whatever the design allowance or performance control system, it will always be necessary to undertake end-of-line measurement and verification so as to check the result of the whole process and to provide early warning of processes drifting out of control.

Central to a successful system will be the adoption by the industry of performance control systems that deliver consistently high performance. The use of confidence factors and post-construction measurement will provide the incentive for the industry to change. In developing a regulatory system post-2016, government policy would need to be geared towards assisting the industry in working towards new processes. This will require investment in research and development, with the Government and industry working in partnership so as to produce process models and measurement methods that deliver acceptable performance for new dwellings. The development of such a partnership and investment programme would require government to lay a solid foundation based on the following:

- a clear statement from government about its determination to have in place by 2016 or 2020 a regulatory system capable of identifying realised energy and carbon performance on a developer-by-developer and site-by-site basis;

- an outline of the mechanism by which the building control system (in whatever form) will verify both effective performance control systems and actual performance in completed dwellings;

- a timetable over which the changes will take place, including legal transitional arrangements;

- a statement of the mechanisms that will be developed to deal with underperformance;

- a programme of pilot schemes in which different approaches to process improvement and control audit can be evaluated; and

- the publication of a series of model process guides based on the findings of the R&D programme.

Feedback mechanisms

All improvement processes need feedback. However, developing effective feedback loops for processes that will deliver zero carbon housing is likely to be difficult. The problem of feedback needs to be tackled at two levels. Level one (micro) should focus on the needs of developers and development teams so that the myriad of detailed learning items are understood and built into revised processes as part of a continuous improvement cycle. Level two (macro) needs to look at the larger picture and is a matter for the Government and the house-building industry as a whole. This level is concerned with gaining feedback on the performance of the overall strategy and the extent to which changes at the micro level are having an impact on the overall improvement at a national scale.

Level one – micro feedback

The micro level is concerned with learning loops both within organisations and from one organisation to another. Although, in many organisations, there are informal feedback loops and 'tips' about how to improve performance are passed around, they are rarely built into design and construction processes. These informal feedback loops tend to be individualised and personal, and, as a result, have little impact on collective improvement. The feedback from Elm Tree Mews to the design and construction of the Temple Avenue prototypes was of considerable benefit and we have already remarked on the development of skills within the Temple Avenue teams. However, it remains to be seen whether the learning that was acquired becomes embedded in the organisational collective or resides only with individuals and is, therefore, prone to loss as people leave.

Level two – macro feedback

As at the micro level, feedback is required on the performance of the industry as a whole and the impact of government regulation and other policies. Such feedback needs to be managed and absorbed by government, the Industry at large and its stakeholders. In many respects the large-scale feedback loops suffer from the same problems as those at the micro level. Despite concerns about the energy performance of dwellings dating back at least to 1998 (see, for example, Lowe and Bell, 1998), the overall energy performance of dwellings has not been measured systematically in either post-2002 or post-2006 dwellings. Work post-2002 was undertaken to establish air tightness in a sample of 99 dwellings (Grigg, 2004), which demonstrated that over a third of dwellings did not meet the standard required (10 $m^3/(h.m^2)$), and did not address the issue of overall thermal performance.

Studies post-2006 have sought to provide feedback on regulatory process issues. The study by Bell, *et al.* (2010b) involving 11 workshops with a total of about 110 building control and industry participants provided considerable insight into some of the difficulties with the implementation of Part L 2006. Of particular note is a general lack of confidence in as-constructed carbon emission rates. In a similar vein, phase two of the study by the Energy Efficiency Partnership for Homes and Communities and Local Government (Trinick, *et al.*, 2009) evaluated 82 SAP 2005 submissions, concluding that some 56 assessments (68 per cent) contained some errors, and that when recalculations were done, just over 20 per cent of the sample failed to meet Part L 2006 criteria 1 (DER <= TER). Those that failed did so with, on average, a designed carbon emission rate some 10 per cent above the regulatory target.[40]

As part of the LowCarb4Real knowledge exchange project, a series of workshops was held to elicit feedback on the barriers to improving the energy performance of UK housing, from a cross-section of professionals from the house-building industry, academics, key stakeholders and policy-makers (Miles-Shenton. *et al.*, 2009). One of the key findings from this work was the perceived need for fundamental improvements to the various processes that will be required to deliver low energy houses that actually deliver their designed performance together with cultural change within the housing industry. The role of performance measurement in these processes was thought to be key, as expressed by one of the workshop participants who worked for a volume house builder:

> *When you end up with evidence, good-quality evidence, then the decisions you make in the future are evidence-based decisions that we can all respect and build on.*

Useful though these ad hoc studies are, they do not provide a comprehensive picture of the performance of dwelling production overall and cannot demonstrate the extent of improvement, if any, from one regulation cohort to another. If government is to be able to chart and steer the zero carbon homes policy, it is essential that detailed and routine macro feedback is provided over a range of key performance indicators, including measures of both fabric and services. Such routine data collection could be derived as a by-product of a revised building control system that collects and audits test data as well as from commissioned research.

Research and development

The evaluation of the Elm Tree Mews scheme has highlighted the need for much greater understanding of the performance of new dwellings, as-constructed. This echoes similar conclusions reached during the Stamford Brook project (Wingfield, *et al.*, 2008). Both projects identified not only specific technical issues such as thermal bypasses and heating system inefficiencies, but also the need for significant research into new design and production processes that are focused on product performance. The learning from Elm Tree Mews has been considerable and there is much that could be achieved from a series of similar studies exploring the issues in different contexts. However, it is likely that a range of different study types will be required that address the emerging research themes. The key research themes that emerge from the work at Elm Tree Mews are summarised in the following paragraphs.

As-constructed and as-installed performance

Much greater understanding is required of what happens to performance when different components are put together into a composite system. Elm Tree Mews has demonstrated that the performance of whole systems, whether fabric or services, will nearly always be less than predicted where predictions are derived from the performance of individual components considered in isolation. Thermal bypasses exist because the air-barrier and insulation components are not well integrated into the thermal envelope as a whole. Similarly, poor air tightness is often the result of a set of air tight components put together using

joints that are extremely leaky. In the case of the communal heat pump at Elm Tree Mews, the buffer tank and distribution pipe-work arrangement together with a complex control requirement and inappropriate pumping arrangements were partly responsible for the poor system performance of the heat pump. It is clear that there is a need for rigorous engineering and scientific research programmes designed to establish the key determinants of as-constructed performance across a wide range of fabric (traditional construction as well as off-site methods) and services systems for low carbon housing.

Processes improvement

Many of the issues discussed have their origins in the processes of design and construction that are used within the industry. Even when off-site construction is adopted, as at Elm Tree Mews, the associated processes remain rooted in approaches and cultures that do not focus on technical performance goals. There remains a great deal of work to establish process blueprints that can be adopted by the different organisations responsible for the design and construction of low carbon dwellings. Such blueprints must be capable of the delivery of robust performance in a way that is objectively verified in completed dwellings.

Methodological development

The methods used at Elm Tree Mews to evaluate performance were rooted in the research domain. They involved significant instrumentation and survey work together with considerable effort to analyse and interpret results. Such methods, in their current form, are not well suited to the needs of production testing and performance verification on a routine basis. The coheating test, in particular, is a powerful research tool but is in need of considerable development before it can be used reliably as a routine part of production processes. It is likely that a mixture of methods will be required, including physical measurement of heat loss at different levels, self-monitoring for particular services systems and robust inspection systems. What is more, the development of methods must be compatible with parallel developments in design and construction processes so that the two become mutually supportive in assuring the performance of completed homes.

Understanding lifestyles, energy consumption and the resident experience

The interactions between dwellings and households and the consequences for energy consumption are complex. The residents at Elm Tree Mews were very happy with their fuel bills but there were other issues raised, some of which would have energy or comfort consequences. The investigations of the resident experience at Elm Tree Mews were largely explorative and although such post-occupancy evaluation studies provide a great deal of insight and raise many questions, it is rare for them to be able to conduct experiments involving different use patterns or to investigate in detail the interactions involved. For example, the question of controls and control complexity was a constant issue among the Elm Tree Mews residents but the study was not able to go beyond describing the general level of bewilderment. There is much that could be done by adopting sound ergonomic principles and research techniques, both in the laboratory and in the field, that could help to address many of the control and controllability issues that have been raised at Elm Tree Mews and elsewhere.

Implications for social housing providers

The implications for social housing providers have two broad aspects. The first relates to their role as developers of social housing and the second to their role as landlords. As developers they should be concerned about the extent to which the industry, on which they rely, is able to produce low carbon dwellings that achieve design expectations reliably and robustly. As landlords, there are implications for

their ability to provide housing that is not only affordable to run but also meets resident expectations. There will also be issues for consideration by those responsible for management and maintenance.

Social housing development

As publicly funded clients, social housing developers are in a crucial position to drive the low and zero carbon housing policy. It is clear from government policy statements that the funding mechanisms will be structured so as to improve energy standards in social housing that are in advance of changes in the Building Regulations. However, social housing developers rely on the same house-building industry as the private sector and are therefore in a position to foster the improvements needed to close the performance gap.

The most important role for social landlords as developers is to act as informed clients on behalf of their tenants. This means that they should require the contractors and private developers from whom they procure new housing to demonstrate how they will assure the actual performance of the product they produce. At Elm Tree Mews a series of searching questions about the detailed design of the superstructure system could have exposed the impact of actual timber fraction and ensured that the required fabric performance was achieved. This was done by the designer of the Temple Avenue scheme to good effect in the case of the structurally insulated panel system used on one of the dwellings. Whether developing via traditional methods or purchasing affordable housing off the shelf, there are reasonable questions that could be asked by an informed customer/client about performance assurance and performance measurement data. For example, some social landlords require a large proportion of dwellings procured on a private sector scheme to be pressure tested. Although this does not provide a full picture of fabric performance, if effectively enforced, it can ensure that the private developer maintains some continuing focus on actual performance. Other performance measurement and testing of fabric and services could be specified as part of the contractual relationship, particularly if done within the context of contract partnering.

Of course it would be naïve to expect the fundamental and systemic problems within the industry to be solved by social landlords making contractual demands. It is likely that, in the short to medium term, it would be difficult for social developers to drive improvements such as an increase in performance measurement or detailed design calculations without risking a considerable increase in costs. However, given the developing concern at national level about regulatory compliance, it is likely that the need for change will be increasingly acknowledged by the industry.[41] Such a shift would provide an opportunity for social landlords to develop a dialogue with partnering contractors and developers that could help both parties resolve the difficulties to their mutual benefit.

Social housing management

The role of social landlords in low carbon housing will be no different to that performed as landlords of other housing. Indeed, as renovation of the existing stock takes place, it is to be hoped that by 2050 almost all the stock will be relatively low carbon compared to current performance. However, the lessons from Elm Tree Mews for social housing providers lie in the understanding provided by residents and in being able to help residents get the most out of their home. This places a premium on the knowledge and training that housing officers are given concerning the operation of heating and hot water systems and also how to advise tenants on the optimum ways of using them. The fact that many of those in social housing may be on lower incomes and at risk of fuel poverty provides a strong driver for social landlords to support the development of energy efficient housing that reduces energy consumption while meeting the needs of residents.

In low carbon housing it is likely that new types of services systems will be used increasingly. The complexities created by the different water heating inputs at Elm Tree Mews were considerable and

devising an appropriate control strategy was beyond even the professional team let alone the residents. Clearly, a much less complex system would have been easier to control and, in all probability, would have provided a more consistent hot water service. Nevertheless, the ability of management staff to explain the operation of the different systems and to provide advice to residents on operational matters was important to the way the dwellings were used. This places a premium on the knowledge and training that housing staff receive of the relationships involved between the technology and the people who use it.

Maintenance staff and contractors will also need to understand the maintenance requirements of the new services and fabric installed and the consequences of maintenance actions. We have commented already on the need for complex low carbon services systems to be designed with an increased performance measurement and self-diagnostic capability. However, such capability will be wasted unless those who maintain the systems are able to access the information and effect repairs or change settings to suit the needs of different residents. It is arguable that the use of communal systems such as those at Elm Tree Mews is more suited to performance checking and effective maintenance. However, the responsibility for communal systems carries financial risk, particularly in relation to the setting of tariffs for the service. In the case of Elm Tree Mews, the setting of the heat tariff is determined, to a significant degree, by the performance of the heat pump. Thus, if performance is less than expected or decreases over time due to a lack of maintenance, the potential exists for increased costs to the landlord.

The existing housing stock

Space does not allow a full discussion of the implications for improvements to the existing housing stock. However, it is important to note that, given existing replacement rates in the UK and other countries in Europe (less than 0.1 per cent, see Hartless, 2003), by far the largest contribution to reducing carbon emissions will be from improvements to the existing stock. Failure to do this could result in dwelling demolition and replacement on a scale that was not seen even at the height of slum clearance in the 20th century. Indeed, some commentators have suggested that large-scale clearance and redevelopment could become a distinct possibility in the near future if renovation policies fail to deliver the required improvement in carbon emissions (Boardman, *et al*., 2005).

It is clear from recent policy discussions such as *Pay as You Save* (UKGBC, 2009) that a great deal of effort is likely to be focused on improving the existing housing stock over the next decade. However, as with the zero carbon new homes policy, there is considerable reliance on modelled performance, which is not well supported by studies of as-constructed performance. Initial results from improvements carried out to an existing dwelling undertaken as part of the Temple Avenue project (Miles-Shenton, *et al.*, in press) indicate that as-constructed performance is likely to be less than modelled. In fact, the problem is likely to be exacerbated because the performance of unimproved dwellings may be better than that assumed in modelling. Thus, assumptions about the extent of improvement are undermined not only by the underperformance of improvements but also by the modelling of the starting point. Clearly there remains a considerable amount of work to establish the problems and difficulties involved in renovation work. It is hoped that the investigations at Temple Avenue and evaluation of the achievement of national schemes will extend knowledge in this area.

End piece

In drawing the strands in this chapter together it is important to recognise that in resolving the difficulties of designing and constructing low and zero carbon housing that performs effectively in almost every case, considerable effort will be required from all sectors of the industry and its stakeholders. Some of the key issues are listed below:

- For government, the key challenge will be in devising a regulatory framework that is able to ensure robust compliance with zero carbon standards.

- For the industry in general, considerable improvement will be required in design and construction processes, changes that will involve a significant shift in industry cultures.

- For the supply chain there are major implications for the design and manufacture of their products. One of the most important drivers of innovation will be increasing demands from designers and developers that require the supply chain to shoulder more responsibility for the performance of its products, as-constructed and installed.

- For educators and the professions, at all levels, the education and training burden will be great. A considerable skill development programme will be required to meet the needs of existing personnel as well as new entrants. The most urgent requirement will be for an increase in the skills of educators themselves.

- For the research community, the task of developing the necessary applied knowledge base will be a large one. In particular, there is an urgent need to develop better understanding of building performance 'as-constructed' in conjunction with improved methods of accurate performance prediction, new production tests and better approaches to process control.

- For social landlords, their development policies and practices can enhance the improvement process and lead the way in improving performance. Their management policies will need to enable residents to operate their home to maximum energy benefit and ensure that performance is maintained in the long term. With the advent of new services systems, the challenges for management and maintenance will be considerable.

7 Conclusions and recommendations

The Elm Tree Mews scheme was a bold attempt to drive forward energy and carbon standards for housing. At the time of its conception and before the advent of the UK Zero Carbon Housing policy, the scheme was 40 per cent in advance of the prevailing regulatory standard (2006 regulatory standard) and is close to the standard anticipated for 2013. It is clear that, at its conception, the scheme was almost ten years ahead of its time and provided a valuable opportunity to learn about the issues involved in the delivery of low and zero carbon housing.

This study should be seen as part of a continuing programme of feedback from real schemes that chart the path towards achieving national goals for low and zero carbon housing. Indeed, schemes that purport to achieve zero carbon housing standards are beginning to be built and it is vital that they learn from research on schemes and, in their turn, receive the same level of scrutiny that has been undertaken in this project. Of course, such as Elm Tree Mews not all attempts will live up to their performance expectations, but it is only by making the attempt and evaluating and publishing the results that lessons will be learned and improvement achieved.

In addition to evaluating dwelling performance, we have sought to address issues that are of systemic relevance to the Industry, the Government, the supply chain and the supporting infrastructure (professional bodies, education and training, research and development and the like). Despite the adoption of a novel heating technology and the off-site nature of the construction method, the performance observed at Elm Tree Mews was the result of a traditional process rooted in existing industry cultures, norms and capabilities. In interpreting the results and reaching conclusions, it is important to understand that the highly skilled project team was working close to the limits of existing technology, supply chain capability and industry processes. Given such a situation, it would be surprising if everything went according to plan and that there was no room for improvement.

Although the scheme fell significantly short of its performance objectives, it is important to recognise that none of the problems are insurmountable. In fact, the seeds of the solutions reside within the identification and analysis of the problems encountered. Given a willingness on the part of the industry to embrace the need for process change, coupled with technological improvements, there is no reason why robust low carbon housing could not be achieved in mainstream house building. Indeed, the experience of the transfer of learning from Elm Tree Mews to the design and construction of the Temple Avenue prototypes demonstrates clearly that by addressing many of the issues identified at Elm Tree Mews a significant improvement can be achieved within a relatively short time frame.

Dwelling energy and carbon performance

Our conclusions on the physical performance of dwellings draw on both post-construction measurement and post-occupancy monitoring. With some exceptions, low energy housing studies have focused on in-use monitoring only in the belief that this delivers a clear understanding of real performance. However, as is often discovered, the inherent variability in household size and many other use factors act to confound the results and it becomes difficult to disentangle energy consumption data. Because this study measured the physical performance of the dwelling fabric and services prior to occupation, as well as monitoring in-use performance, we have been able to 'close-the-loop' between design assumptions

and expectations and our measurements. This has enabled a much clearer understanding of the different factors involved and their contribution, thus extending and deepening the learning.

Normalising for use and applying measured fabric and services data, overall carbon emissions from the scheme as-constructed were estimated to be around 75 per cent higher than estimated at design stage (some 15 $kgCO_2/m^2.a$ as designed compared with 26 $kgCO_2/m^2.a$ as constructed). Energy and carbon performance was similar to that required for a dwelling constructed to 2006 Building Regulations standards. This contrasts with design estimates that anticipated standards proposed for 2013.

Fabric performance

The performance of the thermal envelope of the dwelling was well below that anticipated with a whole house heat loss some 54 per cent higher than design predictions, with an absolute discrepancy of just under 70 W/K (127 W/K designed and 169.8 W/K measured). Almost all of the 70 W/K additional loss was attributable to fabric losses, which means that, when compared with the predicted fabric loss (100.9 W/K), the discrepancy represented an increase in the region of 70 per cent. Detailed investigations showed that the discrepancy was the result of design and construction process factors that:

- underestimated the amount of structural timber in the walls and roof, resulting in increased heat loss (23 per cent of the difference);
- did not account fully for thermal bridging at junctions, openings and other thermal anomalies (25 per cent);
- did not account for heat loss via a thermal bypass formed within the party wall cavities (30 per cent); and
- did not ensure that thermal performance was maintained when a change was made to the supply of windows during construction (21 per cent).

In addition, the original air tightness specification was not carried through into detailed design, resulting in a measured air tightness that was in line with that common in mainstream house building but much lower than would be expected of a low energy/carbon dwelling. The impact of this is not included in the performance assessment but, had the outline design intention of 3 $m^3/(h.m^2)$ @ 50Pa been maintained during detailed design, the designed performance level would have been even lower than that which emerged.

Services performance

The design of the scheme, particularly in reducing carbon emissions, was critically dependent on the performance of the communal heat pump and on the effective operation of the solar water heating systems. Our conclusions on the energy and carbon performance of the services are as follows:

- **Heat pump CoP** The coefficient of performance (CoP) of the heat pump unit, ignoring systems effects, was below the value of 3.2 (whole system) assumed in space heat design calculations. Even when improvements were made to reduce the over-sizing of the hot-side circulation pump and prevent constant running, the CoP increased to only just over 3. The commissioning estimate of 3.5 was well above what was measured at any time during the monitoring period.

- **Systems effects** If all the systems effects are taken into account, including buffer tank and heat main losses, heat main circulation pump energy and control system energy, then the average system CoP was only 2.15 over the twelve-month monitoring period. It is possible that some improvement on this figure may occur in future years as a result of improvements made, but additional monitoring would be required to verify this.

- **Gas boiler v. electric heat pump** The decision to adopt a communal heat pump instead of gas was highly dependent on the CoP of the heat pump system. If the actual system performance were applied (seasonal CoP of 2.15) as opposed to the design assumption (CoP of 3.2) a gas system would have produced marginally less carbon (a saving of 0.1 tonnes CO_2/annum). If the revised (2010) carbon emission coefficients and services and fabric underperformance were taken into account, a gas system would have resulted in about 1 tonne CO_2/annum less than the heat pump. However, given the design expectations for the scheme and the carbon coefficient prevailing at the time, the original decision was well founded.

- **Installation of solar systems** The solar systems suffered from significant installation and commissioning difficulties with only one system out of the six installed that did not encounter either installation or operational problems. Many of the installation and initial performance problems could have been avoided with a more integrated approach to design and installation and more advanced commissioning procedures.

- **Solar system performance** The solar system from which reasonably reliable performance data could be extracted indicated that it was providing a level of solar heat (1,179 kWh) commensurate with that predicted at design stage (1,097 kWh).

- **Hot water system and CoP** The strategic decision to supply heat from the communal system to both space and water heating involved a compromise in flow temperature and will almost certainly have impacted on the CoP of the system. Also, it increased the risk of legionella bacteria in the water system, which resulted in the need for an automatic weekly pasteurisation cycle using the immersion heater.

- **Hot water service** The system design produced a complex mix of heat inputs that were difficult to control, both technically and for the residents. The resulting complexity coupled with the operational difficulties with the solar systems tended to produce a low level of hot water service.

Relationship between residents and their homes

Despite the difficulties with fabric and the efficiency of the heat pump system, the space heating system delivered reasonable internal temperatures and, with the exception of the hall and adjacent toilet temperatures, residents made few critical comments. This was not the case with the level of service from the hot water system, leading to an acceptance of a low level of service and adaptive behaviour to fit in with the weekly hot water pasteurisation cycle. Our conclusions relating to the experience of residents are set out below under the main themes developed from the interviews.

- **Design and resident needs** The general amenity relationship between residents and their homes can have important implications for energy and carbon performance of what is a complex system. The proposed use of electric heaters in the unheated winter garden (which was perceived as a space that added little value in its current form) so that it could be used as dining space is an example of residents adapting their environment but increasing their carbon emissions.

- **Engaging with new technologies** The services installed constituted a complex set of different technologies, each with their own control device. This was bewildering for the residents. Not only was the array of controls confusing, with different buttons and setting processes to contend with, but the fact of having different energy inputs that needed to be controlled made it difficult for residents to understand what approach to control was best.

- **Knowledge and confidence** The level of knowledge and understanding can have a marked effect on resident confidence to change systems and make adjustments so as to match their needs. In the face of confusion over the operation of controls, the general tendency was to leave things set as they were at installation or following specific advice from a researcher or a member of housing association staff.

- **Affordability** There was considerable satisfaction with the affordability of heating, although some concern was expressed about electricity bills. Resident concern about affordability would appear to have influenced their use of the dwellings overall and seems to be influenced by their knowledge and understanding of the way the systems operate. In particular, their use and control of the hot water system, which was difficult to understand, seemed to be problematic with some admitting to having cool baths or not being certain whether there would be hot water available when they wanted it.

The development process

Much of the underperformance at Elm Tree Mews was rooted in the adoption of traditional design and construction processes that were not well suited to the level of detail and performance evaluation that is required for achieving low and zero carbon housing. The design and construction approach was complex, with a large number of subcontractors and specialist suppliers, all of whom created communication requirements that were highly detailed. During design there was heavy reliance on default values and notional assumptions of construction and services performance. Construction presented issues in relation to sequencing, product substitution and commissioning of services, all of which impacted on performance.

Despite the off-site nature of the elements of dwelling superstructure, the approach to detailed design and construction and the prediction of energy performance were not untypical of developments in the mainstream. All those involved in design, construction and commissioning were operating within accepted norms of industry practice, using the information and tools that were available at the time. However, with little change in standard processes, they were seeking to produce energy and carbon performance that was well in advance of current construction.

Our main conclusion from the evaluation of development processes is that designing and constructing robust low and zero carbon housing are likely to require significant changes in the processes used. Such changes are likely to be much greater than those required in technology and probably much more difficult to achieve since process changes are required at every level of the industry and at every stage, from inception to occupation and use. Our detailed conclusions are structured around these different development and use stages.

Procurement and inception

Decisions made early in procurement can have a significant impact on the final development, for it is at inception that the overall approach is decided, design and construction teams established and targets set. In this area we reach the following conclusions:

- The brief for Elm Tree Mews acknowledged the importance of process and the control of quality. However, this does not seem to have been driven to the point of requiring hard performance data from previous schemes or of process descriptions that show how performance would be assured.

- The lack of hard data on previous schemes was not surprising since there is very little objective performance data on low energy housing in the UK. This makes it difficult for those seeking to procure low energy housing since they can do little but base their judgement of proposals on general performance claims. In the future it will be important that those who claim to produce low carbon housing are able to provide objective evidence of as-constructed performance.

- The complexity of the procurement process made it difficult to ensure that all interactions were effectively managed. Of particular importance was the availability of performance information at a level of detail that could be used in design calculations and decision-making. One of the most important effects of such organisational complexity is that it can result in a system of overlapping responsibilities in which boundaries are blurred and accountability difficult to define.

Detailed design

Detailed design is a difficult, and often unacknowledged, part of the design process. This is particularly so in the case of low energy design. To undertake it fully is costly and involves a high level of expertise on the part of the designer. Our conclusions on the process of detailed design are set out below:

- **Design calculation** Thermal performance of the dwelling fabric does not receive the level of detailed scrutiny that would ensure the accurate modelling of performance. The observations at Elm Tree Mews in relation to the use of nominal U-values and the reliance on default thermal bridging values are indicative of a culture in design that seeks to avoid detailed calculation. Such an approach relies instead on manufacturers' claims and generalised values that are used as SAP modelling input. The approach adopted is common practice within house building and has been observed in other studies.

- **Skills** The tendency to avoid detailed thermal calculation is a reflection of a general lack of thermal calculation skills among housing designers. The development of such skills would go a long way to address the difficulties caused by a reliance on manufacturers' claims and the use of default values.

- **Information** The responsibilities for accurate information and accurate calculations are often diffuse. At Elm Tree Mews, the proportion of timber in the walls and roof was a significant element in calculating U-values but there appeared to be uncertainty about the responsibilities for supplying and applying this important data. Detail design processes need to ensure that these responsibilities are clarified.

- **Supply of fabric systems** Where manufacturers are supplying a complete system, as in the case of the walls and roof at Elm Tree Mews, there is a strong case for requiring the manufacturer to take full responsibility for energy performance alongside other aspects such as structural integrity.

- **Thermal bypassing** There is a critical need for designers to address all forms of thermal bypassing in detailed design and to ensure that this is given full consideration alongside other aspects of heat loss.

- **Geometric complexity** The geometric complexity of the thermal envelope is a key element in the ease with which thermal bridging can be minimised and air-barrier continuity maintained. Where complexity is a consequence of other design requirements, this should be recognised in the design process so that sufficient design resources are available to resolve difficult junction details.

- **Low and zero carbon systems design guidance** The detailed design of heating and hot water services in general, and low carbon systems in particular, is hampered by a lack of modelling capability, design guidance and data on the performance of whole systems. Energy modelling is

dominated by expectations about the efficiency of the main component, such as a heat pump or boiler, but does not take into account whole systems performance as manifest in a particular set of circumstances.

- **Services complexity** Services design complexity, as characterised by the hot water system at Elm Tree Mews, is likely to be counterproductive since it brings significant control complexity that is very difficult to design and, just as important, difficult to use.

- **Services self-diagnostic capacity** In a number of cases at Elm Tree Mews the installation problems with the solar hot water systems were only discovered because of the monitoring. This applied also to errors in settings and timings for other services. Although it could be argued that some of the problems should have been picked up in commissioning (see below), this would not be true of all. Similarly, the monitoring information provided during the project assisted in making important improvements to the operation of the heat pump system. It is clear that domestic systems, particularly low and zero carbon systems, need to have some built-in capacity to monitor their own performance and to identify faults. Such self-diagnostics would be invaluable for maintenance purposes.

Construction

The level of underperformance that could be attributed directly to the control of the construction process was less than that related to design. This is relatively unusual, and other studies have identified a more mixed picture. However, there were a number of areas in which improvements in the control of the construction phase could have avoided some of the underperformance observed. Conclusions in this respect are as follows:

- **Off-site production** Despite the off-site nature of much of the thermal envelope it was not immune from process control problems. Some of the difficulties and delays in the construction programme were attributed to the erection of the timber frame and difficulties in controlling the erection process. Although it had little impact on thermal performance, it serves as a reminder of the importance of close control over design, manufacture and construction on site.

- **Product substitution** The processes by which product substitutions are made can have a significant impact on performance. The problems encountered stem from the lack of a clear process that both identifies the key performance characteristics to be achieved and verifies that the new product satisfies the specification.

- **Planning and sequencing** Construction planning and sequencing are crucial to ensuring that details can be constructed robustly. As with product substitution, this is a matter of both design and construction. The level of detailed planning required to ensure that construction is carried out effectively is considerable and will become increasingly important for low carbon dwellings.

- **Commissioning** Commissioning processes for heating and hot water services are not sufficiently robust to establish that systems are working effectively and performing as expected. In the case of both heat pump and solar systems at Elm Tree Mews, there were installation problems that could have been identified at the commissioning stage if more rigorous testing had been undertaken as part of commissioning procedures that were more robust.

Understanding resident–dwelling interactions

The ability to identify, from post-occupancy studies and other forms of resident feedback, the key interactions and the energy consequences of use is crucial to improvements in low carbon dwelling design. The feedback from residents at Elm Tree Mews echoed a number of themes that are common in post-occupancy evaluation. General issues such as spaces that do not seem to function as residents would like or lack of storage space are mingled with more specific energy-related issues based on problems with complicated controls and particular control devices that are not very intelligible. The underlying concerns relate to the way in which the interactions between residents and their homes are understood and taken into account in design. Our principal conclusions in this respect are set out below.

- **Control devices** The design of control devices is often not intuitive and would benefit from a more user-orientated approach. Similarly, the advent of low carbon systems for space and water heating together with zero carbon energy generation can produce an array of different control devices with different approaches to display and operation. The result is a confusing picture, which prevents, rather than enables, effective control. In order to tackle this problem, device and system manufacturers need to pay more attention to the ergonomics of the displays and controls they design, but, just as importantly, dwelling designers need to improve the design of the control ensemble overall to prevent confusion.

- **Design and use assumptions** Expectations about how residents will use their homes and the lifestyles that the home is designed to support, are not made explicit in design. Without an explicit understanding of use and its energy consequences, it is difficult for designers to imagine different scenarios and test their designs. In addition, the usefulness of feedback from residents is diminished by the lack of a clear idea of what the design expectations were in the first place.

- **Post-occupancy evaluation** The evaluation of low and zero carbon housing schemes requires a clear understanding of the interaction between residents and their homes in general and the impacts on energy and carbon performance in particular. This needs to be played out in some detail if the relationship between residents and their dwellings is to be understood. The feedback from such studies would be particularly valuable, not only in the design of things such as controls, but also in helping to frame design methods based on lifestyle scenarios and interaction models that help predict likely relationships and their energy and carbon consequences.

Continuous improvement – micro feedback

Feedback is crucial to improvement but it has to be sought, garnered and acted upon. To a large degree, the culture of assuming that what is constructed is consistent with what is modelled, is the result of a lack of feedback. If the performance gap is to be closed it is important for the house-building industry to seek and analyse, as a matter of routine, energy and carbon performance data so as to establish a continuous improvement loop. From the limited experience of providing feedback from Elm Tree Mews to the Temple Avenue scheme we have concluded the following:

- The provision of feedback, which included both design and construction process lessons, resulted in whole house heat loss of the Temple Avenue dwellings that was within 10 to 15 per cent of that predicted in design calculations.

- If feedback is to become common and shared across the industry, ways must be found to avoid a claims-orientated approach, particularly during the learning phase between now and the implementation of the Government's zero carbon housing standard post-2016.

Recommendations for change

Our reflections on the implications for government, housing providers and other stakeholders have led us to consider the nature of the change required and how this may be instigated. This final section sets out our recommendations for change drawn from the discussion in Chapter 6.

Government concern is increasing about the existence and extent of a significant gap between predicted performance, which is represented in regulatory submissions, and that realised in practice. Also, there is a developing realisation within government and among stakeholders that change is required to the way regulation is framed, performance verified and design and construction processes undertaken within the industry at large. Recent advice from the Zero Carbon Hub, in a report commissioned by the Government (ZCH, 2010), is indicative of this developing realisation.

Our studies at Elm Tree Mews and elsewhere suggest that fundamental change is required in practices and cultures across the industry. What is required is little short of a re-engineering of industry processes from inception through design to construction and occupation. Such change will involve not only those designers and developers on the front line, but also the supply chain and its supporting infrastructure of regulators, educators, the professions, skills councils and the research and development community. By way of recommendation, we propose a programme of change for the next five to ten years that focuses principally on process improvement across the industry, involving the effective use of performance feedback and supported by improvements in technology, scientific understanding of as-constructed performance and the industry's skill base. Figure 42 sets out the elements in such a programme and the following sections provide an outline of the key components.

A partnership

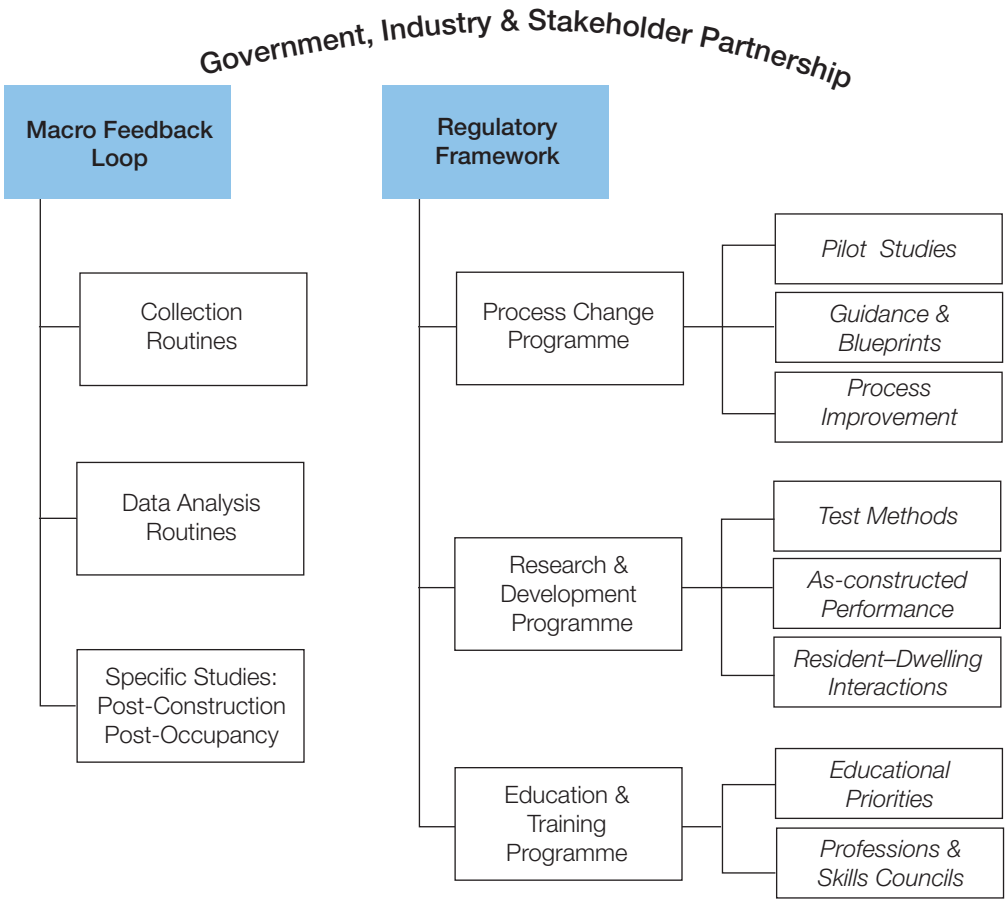
No programme for change will be possible without a clear sense of partnership involving government, the industry and its stakeholders. Such a partnership is beginning to develop through the Zero Carbon Hub, which was set up by industry and government in 2007 with the express remit of developing the road map to zero carbon housing in 2016. The work undertaken since its inception has sought to build such a partnership and to develop a consensus on the nature of the targets, the difficulties of achieving them and the programmes that should be adopted. The work at Elm Tree Mews relating to the extent of the performance gap has been high on the Hub's agenda and provides a useful vehicle for developing not only change programmes but also the consensus necessary for change to be embraced. Evidence of a developing consensus for change is provided by the recent report of the Carbon Compliance Tool Policy Assumptions Task Group (ZCH, 2010) and it will be important to build on this consensus in driving change.

The first task of such a partnership will be to establish a clear timeline to closing the gap. Such a timeline should be geared to the existing objectives of zero carbon new housing and review the existing timelines to zero carbon. It is likely that, to achieve the extent of change required, the five years to 2016 will not be sufficient. However, it will be important that the programme does not drift without a clear end point or intermediate staging posts. In our view, the existing 2016 target date for implementation of zero carbon should remain, but it would be unrealistic to expect the performance gap to be closed within that time. It is more likely that 2016 would form an important staging post that shows some closing of the performance gap and establishes the standard that housing providers will be required to achieve in design. The five years between 2016 and 2021 should provide an extended transition period that aims to close the performance gap completely and be the point at which strict compliance measures will be implemented.

Developing the macro feedback loop

As discussed in Chapter 6, there is an urgent need to develop the macro feedback loop that produces performance data on a routine basis so that progress towards zero carbon goals can be charted and

Figure 42: Closing the performance gap – a programme for change



changes made to policy implementation and unintended consequences trapped as early as possible. Maintaining the feedback loop in the long term will be crucial to both closing the gap and, just as important, keeping it closed. One of the key strands in the change programme will be developing the feedback programme. Such a programme should involve the development of routine performance data collection that is broadly based, incorporated into the routine processes of building control and, where possible, include resident–dwelling interaction issues as well as physical performance of fabric and services.

Technological changes in information gathering will undoubtedly provide a useful facility, and the advent of so-called smart meters and the ability to provide resident feedback will need to be taken into consideration. However, the application of such systems also raises a whole set of ethical and moral issues. Inevitably, it will be necessary to tackle such problems, which may bring a raft of regulatory and other changes to legislation on the collection and use of data. These issues will not be trivial and resolving them may be as difficult as making changes to design and construction processes.

In addition to routine data collection, there will be a requirement for a programme of specific studies, undertaken both post-construction and post-occupation, so that particular issues identified through routine feedback can be investigated in detail and problems addressed.

Developing and supporting a new regulatory framework

The most important starting point for developing the process change programme will be a new regulatory framework such as discussed earlier. Government and industry should begin work immediately on a revised system. Such work should take as its staring point the recent Zero Carbon Hub proposals (ZCH, 2010; Bell, *et al.*, 2010a) and, working with industry, government should lead the development of a system that provides a level commercial playing field for all who produce new housing. The critical element will be a system that makes it commercially beneficial for designers, developers and the supply chain to invest in process improvement.

A programme of process change

Fundamental process change will not be easy to achieve. Although it is common to evoke parallels with other manufacturing industries, such as the motor industry, it must be recognised that construction is a different manufacturing domain with its own particular problems to overcome. However, it is important to stress that construction is a manufacturing industry and, contrary to conventional wisdom in some construction circles, is amenable to process and performance control. Indeed, the principle of off-site construction is rooted in the notion of improved control using factory methods. In tackling process change that evokes the general notion of manufacturing systems engineering and performance control, the special characteristics of construction need to be understood, processes redesigned and tested, and the performance of the product (housing) used as a benchmark of process effectiveness.

A process change programme should seek to undertake a series of process studies that are rooted in real housing schemes, are outcome focused, trace the complete design and production process, work closely with the supply chain, and measure and evaluate what is produced both prior to and during occupation. The programme of process studies should be cyclical and used to develop process blueprints and guidance for others to use and evaluate as part of the programme. The number of cycles and the range of studies needed to provide enough confidence for replication is not clear, but such a programme should contemplate an initial phase that is at least five years but with more frequent dissemination of interim results and feedback. Also, it should seek to cover as wide a range of common technologies and construction methods as possible, ranging from traditional on-site construction to off-site methods, and including both common service technologies and low, zero carbon and renewable technologies.

A research and development programme

The process change programme will constitute a central research and development effort, in its own right. However, it will need considerable support from a more traditional R&D approach. Such a programme will need to focus on the three supporting areas (test methods, as-constructed and systems performance and resident–dwelling interaction). This programme should be integrated with the process change programme so that the two elements are mutually supportive. One of the most important practical outputs from an R&D programme should be a series of guidance documents, modelling tools and measurement protocols that are of direct application to design, construction and management. As in the case of process change, this should be conceived initially as at least a five-year programme delivering a constant supply of outputs.

A skills development programme

In discussions with the industry about the reasons for energy and carbon underperformance, the need for an improved skills base is a recurring theme. However, there is no clear idea as to what improvements should take place or how they should be achieved. In our view there is an urgent need for a national strategy that makes clear the nature of the skills required and sets out a programme that marshals the resources and begins the task of developing skills. Such a programme would need to set priorities within the context of national vocational education and qualifications and this may require some considerable resource shifting within the education sector. In other areas such as sector skills councils and the professional bodies, a great deal of attention should be given to the development of specific competencies, curricula for courses and continuing professional development. Perhaps the most important factor in a skills programme will be the extent to which the skills being developed are integrated with the central drive for performance-focused process improvement. As in other areas, this places a considerable premium on ensuring that the skills programme is in tune with the other parts of the whole change programme.

The role of social landlords

As housing providers of a significant number of new dwellings, all of which involve the private housing sector either as contractors or as commercial developers, social landlords are in a unique position to influence industry practice. Also, given their role not only in development but also in the long-term management of housing, they are well placed to improve our understanding of how to ensure that households are able to meet their lifestyle needs while minimising carbon emissions in the long term. Given that social landlords provide affordable housing for those on the lowest incomes, they are also central to tackling problems of fuel poverty and this is a key driver in both the development of new housing and the improvement of existing stocks. Social housing providers should be encouraged to use their influence in the following ways:

- As an agent for change they should seek to drive process improvement within their partner organisations, whether that be in the procurement of new dwellings or in the maintenance and renovation of existing stock. Such a role should be recognised in funding arrangements.

- As managers of housing stocks, social landlords should evaluate the extent to which they can work with their tenants to help them improve their understanding and use of their homes so as to reduce fuel bills while maintaining acceptable levels of comfort in both new and existing dwellings.

- As technological innovators they should collate and share experience on the care and maintenance of novel technologies so as to provide feedback and effect improvements.

Funding the change programme

The resources required to effect change will be considerable. In seeking to fund the necessary investment it is important to remember that such funding cannot be seen as the responsibility of society at large through government resources. As pointed out above, the development of change is the responsibility of the industry as a whole, working in partnership with the Government and other stakeholders. It will be the role of government to set the framework and to contribute to work that underpins process improvement and provides for the development of the skill base. However, the development of improvement processes can only be undertaken through industry investment in its own developments. If set correctly, the commercial imperatives of a new regulatory framework that not only sets zero carbon standards but also ensures compliance will drive the need for significant investment by the industry itself. However, such investment needs to be orchestrated, at least through the developmental period, on an industry-wide basis. To do otherwise would risk significant repetition within the programme and, in a competitive marketplace, reluctance on the part of many organisations to share experience and data. For this reason it will be important that the Government works with industry to set up and control the funding streams that will be required.

Notes

1 The formal research programme did not begin until JRF approval of the funding in January 2008; however, construction observations began in March 2007.

2 Monitoring of the communal services (ground source heat pump) and three dwellings was undertaken for just over twelve months with a further two dwellings monitored for nine months.

3 The regulatory target standard is set at the energy and carbon requirements for code 4 of the Code for Sustainable Homes (CLG, 2008a; CLG, 2009a). This anticipated a 44 per cent reduction in carbon emissions compared with the 2006 target level. In the case of Elm Tree Mews the target was set based on the applications of an electricity fuel factor, which sets a higher emission-rate target than for gas. If compared with a gas target the reduction would be some 30 per cent to 40 per cent depending on dwelling type and size.

4 JRHT has planning approval for a 540-house scheme called Derwenthorpe on land adjacent to Osbaldwick in York.

5 Ecohomes (BRE, 2006) was an environmental rating system for dwellings developed by the Building Research Establishment with support from the UK Government. This system was used as the starting point for the Code for Sustainable Homes, which has now replaced it.

6 The terminology used for 'efficiencies' of heat pumps and for other systems can be confusing. Indeed the overall annual (seasonal) coefficient of performance of a heat pump is often referred to as a 'seasonal performance factor' (SFP) and expressed as a percentage or as a real number. In this report the term CoP will be used but, where appropriate, its equivalent in percentage terms will also be included.

7 The final design SAP data sheets treat the dwellings as if they each had their own heat pump rather than a communal system. This resulted in some uncertainty over the most appropriate treatment on CoP for the hot water system, which is a mixture of heat pump, immersion heater and solar thermal. In this report a general design value of 2.3 is used as the benchmark figure for heat delivered to the dwellings. Input from the immersion heater is treated separately.

8 Unless otherwise stated, all references to the Building Regulations refer to those for England and Wales. Scotland and Northern Ireland have their own regulations.

9 In all cases the base line is the 2006 Target Emission Rate (TER) calculated in accordance with the national calculation methodology as specified in the 2006 Building Regulations and has units of $kgCO_2/m^2.a$. The TER is specific to a particular dwelling since it takes into account the size and form of a particular dwelling or dwelling type under consideration. Thus the 2016 target for a specific dwelling would be derived by calculating the 2006 requirement and applying the 70 per cent reduction.

10 The carbon emission requirements of code level 5 specify a zero carbon emission rate in relation to all aspects of use with the exception of household appliances such as televisions, washing machines and the like. Code level 6 takes the final step to zero carbon by including steps to mitigate the impacts of appliance-use through the provision of carbon free electricity supply so as to achieve a net zero annualised emission rate.

11 Ideally, the action research approach adopted would have included research team involvement as participant observers during the briefing, design and construction processes. This would have enabled a richer understanding to be gained by linking the findings of performance monitoring to the processes that produced them. However, as construction had begun by the time the research project commenced, this was not possible.

12 Of particular value in establishing the designed energy and carbon performance was an analysis of the energy modelling undertaken using the National Home Energy Rating (NHER) Plan Assessor software version 4.0.28.

13 More detail of the approach used and the resulting estimates is provided in Chapter 3, and in the technical report (Wingfield, *et al.*, 2010).

14 In Wingfield, *et al.*, 2008, heat loss measurements in six unoccupied dwellings revealed variations of between 70 per cent and 110 per cent higher than predicted from standard calculations.

15 The coheating test methodology was first devised in the USA to explore energy efficiency issues following the energy crisis in the 1970s (Sonderegger and Modera, 1979; Sondereger, *et al.*, 1980) and has been used on a number of occasions in the UK. The technique used at Elm Tree Mews was based on the application of the method for testing on the Stamford Brook development (Wingfield, *et al.*, 2007) and is detailed in the technical report.

16 The result data showed, however, that heat loss through the party wall cavity was sufficiently large to prevent heat transfer from one dwelling to the next despite the three to five degree difference between the test dwelling and the adjacent dwelling.

17 In response to the European Union Performance of Buildings Directive (EU, 2002), the Building Regulations for England and Wales adopted the Standard Assessment Procedure (SAP 2005) as the national calculation methodology (NCM) for dwellings. SAP 2005 (DEFRA, 2005) is an implementation of the Building Research Establishment Domestic Energy Model (Anderson, *et al.*, 2002), which seeks to estimate the average energy consumption and carbon emissions over an annual cycle given certain general assumptions about occupancy and usage. The latest version is a monthly model (SAP 2009) and will replace SAP 2005 as the National Calculation Model when modified regulations come into force in October 2010.

18 In deriving a measure of whole house heat loss it is important to adjust the raw data to account for the amount of solar energy that the dwelling receives. In this way the total amount of heat energy (solar energy plus electrical energy) required to maintain a constant internal temperature is measured.

19 An explanation of the thermal bypass mechanism is provided in the glossary and illustrated in the technical report (Wingfield, *et al.*, 2010).

20 Until the advent of work on the Stamford Brook field trial by the Leeds Met team (see Wingfield, *et al.*, 2008 and Lowe, *et al.*, 2007) the existence of heat loss via the party wall was not recognised and, by convention, party walls were given a heat loss of zero on the assumption that both sides were heated to the same temperature.

21 The thermal bridging y-value could be said to account for some of the non-party wall thermal bypasses that almost certainly exist but since it was not possible to do an exhaustive thermal bridging analysis on all junctions it is not possible to estimate the likely split.

22 All pressurisation test results in this report are quoted at a standard test pressure of 50 Pascals (Pa) in accordance with European standards. In order to reduce the length of the unit text the pressure is omitted in most cases.

23 The 2006 revision to the Building Regulations required some sample testing to be undertaken for the first time. However, there is no centralised database of test results submitted to building control. The data from NHBC (2008) is not a random sample and may have a systematic bias since it is unclear whether it includes all test results that may have been above the Building Regulations maximum. The 2002 results are for a sample of 99 dwellings but again this is not a random sample, although all test results are included in the data set.

24 In interpreting annual data it is important to remember that for Houses D and E monitoring was possible for nine months from January 2009 to September 2009. In order to derive annual figures, estimates had to be procured by extrapolation for the months of October, November and December 2008.

25 Stamford Brook Houses A and C are end-terrace dwellings and B is a mid-terrace.

26 In undertaking the analysis at the level of heat input, the comparison avoids the complexities introduced by a variable heat pump CoP. This approach focuses attention on the impact of fabric underperformance with the dwellings in occupation.

27 The particular reasons for the lower figures are different for each dwelling. However, in both cases occupancy is higher than in the standard SAP assumptions, which increases metabolic heat gain and reduces the delivered heat requirement. In one case temperatures are lower than in the standard assumption and in another the ventilation rate is lower. Both factors would act to reduce the delivered heat requirement. Other factors such as actual differences and assumed external temperatures also have an effect. In general, almost all differences between standard assumptions and actual usage tend to reduce the requirement for delivered heat compared with a standard case.

28 For the purposes of this discussion, this data was supplemented as necessary by manual meter readings for the unmonitored dwelling (House F) that was occupied for only a few months towards the end of the monitoring period and extrapolated data where monitoring data only covered eight or nine months.

29 The carbon coefficients for gas and electricity are estimated from the carbon content of the different fuels and other factors such as transport of the fuel to the point of use. The coefficients to be used for regulatory purposes are published in the national calculation methodologies (from October 2010 – SAP 2009, see BRE, 2010). The coefficients are subject to change as information is updated. Electricity is subject to much greater change than gas since it is very sensitive to variation in the national fuel mix for electricity generation. The latest figures are published in BRE (2010) and calculated in accordance with the methodology used for SAP 2005 (Pout, 2005) and applying updated data on fuel mix etc.

30 The efficiency of 85 per cent for a condensing boiler is used in this analysis since it reflects a more realistic measure of as-installed performance (Carbon Trust, 2007; Orr, *et al.*, 2009; Wingfield, *et al.*, 2008).

31 Dwelling E has a floor area that is a third less than the mid-terrace dwellings A, B and D.

32 Although the solar systems in most dwellings were not operating optimally, it would be expected that as insolation increased through spring and summer and the installation problems were resolved, there would be an increased solar input.

33 This change involved replacing the existing internal circulation pump within the heat pump unit for a set with lower power. Improvements were made also in the control system to turn off the hot-side pump when it was not required. The standard pump set was designed on the assumption that it would need to pump fluid around the whole system but since the actual design included a buffer vessel and the heat main had its own circulation pump, the standard set was considerably overpowered. The improved pump CoP following the change is apparent in the measured data, albeit it took about a month to stabilise at a higher level.

34 The winter garden is a room between the main lounge and the garden and was included in order to provide some energy benefit. In the winter it would harness some solar heat, which would both buffer the heat loss from the lounge and provide a source of passive solar energy. Since the space was considered to be outside the thermal envelope, no provision was made for heating. However, the nature of the site, which is shaded by a tree belt on the boundary, reduces the availability of solar energy in the winter and the lack of heating makes it a difficult space to use during the winter months without the use of portable heaters.

35 This problem has been recognised in the 2010 revision to the Building Regulations and its supporting national calculation methodology (SAP 2009). The statutory guidance requires a more detailed calculation of thermal bridging and includes the use of confidence factors for thermal bridging calculations.

36 In contrast to Elm Tree Mews, the panel system used at Temple Avenue was one in which the insulation formed a polyurethane foam core, which, when combined with timber sheet material, creates a composite structure that minimises the amount of conventional structural timber penetrating the insulation. It is arguable that, from a material sustainability point of view, a polyurethane core would be less desirable than the cellulose fibre used at Elm Tree Mews but the structural and thermal benefits of SIPS were given greater priority in this case.

37 Part L 2006 refers to commercial schemes and the as-constructed performance is based on fabric measurement only (Wingfield, *et al.*, 2009). Temple Avenue is also based on fabric performance only (Miles-Shenton, *et al.*, 2010). The performance of the Stamford Brook (Wingfield, *et al.*, 2008) and Elm Tree Mews schemes is based on fabric measurement and services performance in use. For the purposes of comparison all estimates have been normalised to a typical 80m^2 semi-detached dwelling under standard occupancy assumptions and with the design and measured characteristics of the schemes investigated.

38 Data sources: Wingfield, *et al.*, 2008; Wingfield, *et al.*, 2009; Wingfield, *et al.*, 2010; Sigma House – Stevenson and Rijal, 2008.

39 Part L (conservation of fuel and power) is the section of the regulations that sets out the requirements with respect to energy and carbon performance.

40 This was done if there were two minor errors or one major error.

41 For example, see the consultation in 2009 on Part L of the Building Regulations, CLG, 2009b.

Glossary

Air permeability: The physical property used to measure the air tightness of a building. It is representative of the leakiness of a building with respect to air. The higher the air permeability, the leakier the building. Air permeability is defined as the air leakage rate per external envelope area of the building at a reference test pressure difference of 50 Pa for the inside of the building relative to the outside. The units of measurement are $m^3/(h.m^2)$. This is airflow in metres cubed per hour through the building envelope per metre-squared of external envelope area. Air permeability is measured using a blower door.

Carbon emission coefficient: A factor to calculate the carbon dioxide emissions due to the consumption of various fuels such as grid-supplied natural gas, bottled propane, electricity from the national grid (taking into account fuels used in generation, efficiencies at the power stations and characteristics of the transmission system) or biofuels. The factor takes into account all carbon dioxide emissions to the point of use. The units of measurement are $kgCO_2/kWh$. This is kilograms of carbon dioxide per kWh of delivered energy. Sometimes called the carbon emission factor.

Coefficient of Performance (CoP): A measure of the energy efficiency of a heating or cooling device such as a heat pump, boiler or air conditioning unit. The higher the CoP, the better the efficiency of the device. CoP is unit-less and is calculated from the ratio of work or useful energy output from the device relative to the amount of work or energy input needed to run the device. A CoP of 1 means that the device has an effective efficiency of 100 per cent. If the CoP is less than 1 then the efficiency is less than 100 per cent and if it is more than 1 then the efficiency is greater than 100 per cent.

Dwelling Emission Rate (DER): The DER is the carbon emission rate for a dwelling as calculated using the national calculation methodology (SAP). The units of measurement are $kgCO_2/m^2.a$. This is kilograms of carbon dioxide emitted from the building per metre squared of floor area per annum.

Mechanical and Electrical (M&E): This refers to the components and systems in a building that provide the various services such as heating, hot water, cold water, lighting, electrical supply and ventilation.

Standard Assessment Procedure (SAP): SAP is the national calculation methodology used to calculate the energy performance of new dwellings. The model was originally developed by the Building Research Establishment (BRE) and has been continually adapted to reflect changes in the requirements of the Building Regulations. The latest version is SAP 2009, which was updated to reflect the changes that resulted from the 2010 review of Part L of the Building Regulations.

Target Emission Rate (TER): The TER is the regulatory target carbon emission rate for a dwelling as calculated using the national calculation methodology (SAP). The units of measurement are $kgCO_2/m^2.a$. This is kilograms of carbon dioxide emitted from the building per metre squared of floor area per annum.

Thermal bridge: A thermal bridge is created in an external building element when there is a pathway for heat flow through the element that avoids or short-circuits the designed insulation layer. Thermal bridges occur at junctions between elements such as wall corners. These are called geometric thermal bridges. Repeating thermal bridges occur in regular patterns such as the case of conductive steel wall ties penetrating through an insulation layer in a wall cavity. Non-repeating thermal bridges will arise due to specific design features such as a combined steel window or door lintel that will bridge the insulation layer.

Thermal bypass: A thermal bypass is heat loss due to convective heat flow that arises where moving air can bypass the designed insulation layer. This commonly occurs in building designs at locations where the designed insulation layer and air barrier are not in contact with each other or where there are breaks in either the insulation layer or air barrier. For example, cavities in separating party walls between dwellings can give rise to a thermal bypass because the party wall cavity will continue past the level of the ceiling into the attic, thus allowing the flow of heated air to bypass the insulation in the ceiling.

U-value: A measure of the flow of heat through a building element such as a wall, floor or ceiling. The lower the U-value, the better the insulating ability of the building element. The units of measurement are W/m^2K. This is Watts of heat flow per metre squared area of building element per degree Kelvin temperature difference between the two sides of the building element.

y-value: A measure of the overall effect in a dwelling of the flow of heat through all the known thermal bridges. The units of measurement are W/m^2K.

ψ-value: A measure of the flow of heat through a linear thermal bridge created by a junction between elements such as a wall corner, roof eaves or window reveal. The units of measurement are W/mK. This is Watts of heat flow per metre length of the junction per degree Kelvin temperature difference between the two sides of the junction.

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The views expressed in this report, together with any errors or omissions, are those of the authors. The report does not purport to represent the views or policies of the Joseph Rowntree Foundation, the Housing Trust or any other individual, group or organisation involved in the project.

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This report does not provide any specific guidance on the design or construction of any particular scheme or development and the authors can take no responsibility for the use of the material in any specific context.

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