REPORT BASED ON WORK UNDERTAKEN FOR THE TECHNOLOGY STRATEGY BOARD

AN EXPLORATION OF DATA NEEDS AND EXPLANATORY POWER: RELATIONSHIP BETWEEN FABRIC AND HOUSEHOLD ENERGY USE

FINAL REPORT

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Preamble: Recent developments.

The analysis of in-use energy data contained within this report builds on the initial Stamford Brook research project, which has become seminal in the understanding of building fabric performance. Early work led by Lowe, Bell and Roberts (2003) introduced field tests and tools to understand the building fabric's thermal characteristics. Refined versions of these methods, including whole building heat loss analysis (to establish the heat transfer coefficient), air tightness tests and building forensics now form part of the portfolio of methods commonly used to understand the thermal performance of building fabric (Johnston *et al*. 2012; Gorse *et al.* 2012; 2013; Bauwens, 2015).

More recently, the relationship between building fabric and energy used during occupation has attracted interest (see EBA Annex 71). Of particular interest is investigating whole building energy efficiency through disaggregating in-use energy data, by fabric performance, efficiency of services and occupant behaviour, (Figure a1). Measuring buildings in-use can be challenging, as energy use is affected by user behaviour and environmental factors, such as wind, temperature and solar irradiance.

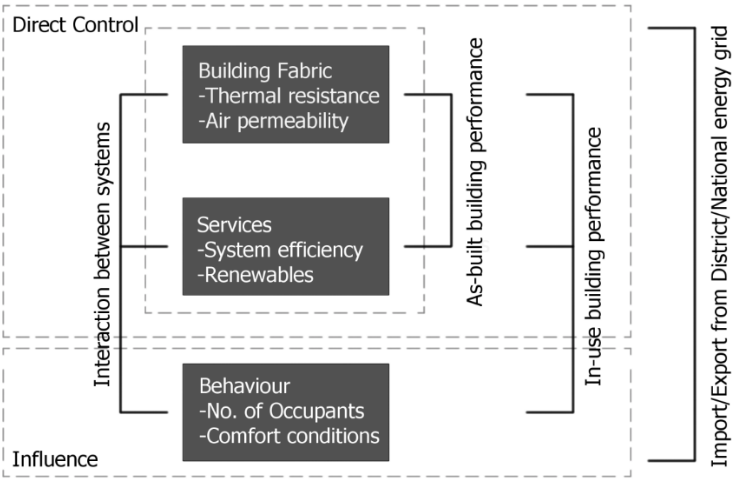

Figure a1. Key attributes of building energy demand

Characteristic variations of energy use as a response to changes in external environmental conditions are referred to as energy signatures. Energy signatures may be associated with either the building fabric or the services in the building. Scientific tests of unoccupied buildings (such as the electric coheating tests), can provide information on the fabric performance of a building. However, detailed fabric energy performance data gathered in unoccupied buildings under test conditions can be difficult for the public to relate to. It is expected that smart meters will eventually be able to process similar information in occupied buildings, breaking down information into component parts (Figure a2) which may be more easily relatable for building occupants.

Dynamic analysis, such as the Saint Gobain QUB test can measure buildings over short periods. It may be possible to extract information during short unoccupied periods or overnight. So far, it has proved difficult to establish algorithms to extract relevant data during standard in-use periods.

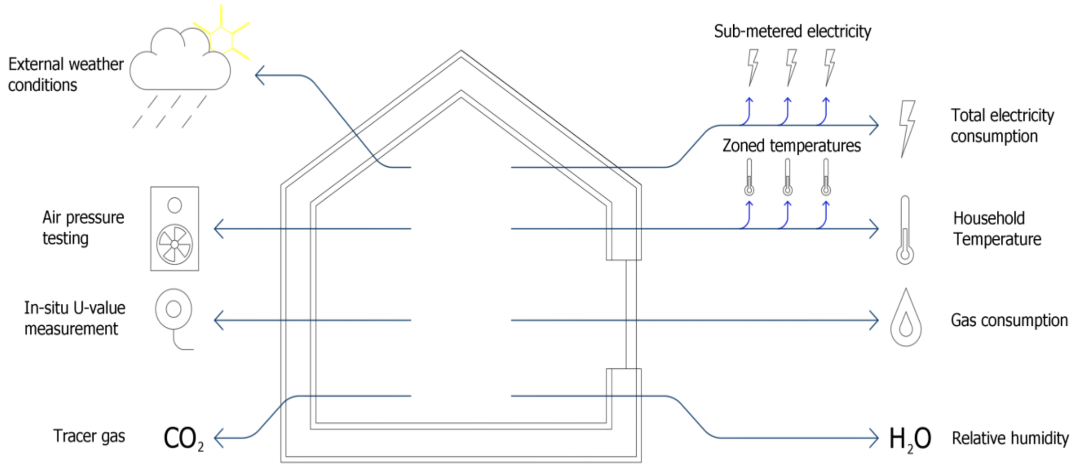

Figure a2. Disaggregated building performance data

While it is clear that relationships do exist between a building's thermal response (resistance and capacity) and energy use, studies of in-use data have failed to adequately (reliably) disaggregate the energy signatures strongly associated with the fabric. However, analysis methods and computing power continue to improve, thus the ability to disaggregate data is also improving.

Identifying energy signatures related to building fabric and building services requires a large quantity of data. Separating relevant information from background variations due to non-performance related energy consumption requires a deep understanding of building performance, occupant behaviour and the building context. This report represents an early attempt to determine the fabric performance of domestic buildings using in-use monitoring data. Fabric performance of the buildings monitored was already known, as they were tested in earlier Stamford Brook reports (see the references for the full list of reports).

The relationship between fabric performance and energy use patterns in this study was limited by not knowing the efficiency of the heating systems. Recent work suggests that with this information, the ability to predict energy use significantly improves. Monitoring heating system efficiency; by using heat meters to measure heat output, in addition to monitoring energy use, will allow more accurate calculations of the thermal capacity and resistance of building fabric.

In the study reported here, it is surprising that any relationship was found between the fabric and energy use without knowing the efficiency of the heating systems. However, differences in fabric and systems performance were evident in this study, especially in cases where fabric alterations had been undertaken or building services were not operating correctly.

With effective building assessment, monitoring and knowledge of building heating systems and services, it is possible make reasonable predictions of energy use and detect problems with building fabric and services. Further work is necessary to understand how accurate such data can become when used as part of a smart building system. Understanding of the variables outlined below and their contribution to building energy consumption is crucial if nearly zero energy buildings are to be realised.

Energy used

Variables

In-use consumption =

V_1	fabric performance (resistance and capacity)
V_2	heating and cooling system efficiency
V_3	occupancy effects
V_4	white goods & circuit load contribution
V_5	environmental conditions

Recent work undertaken by the Leeds Sustainability Institute, has shown an ability to predict fabric performance from energy data where the efficiency of heating systems are monitored and known. Dynamic studies that look at heat-up and cool-down periods suggests that information about fabric and service performance can be obtained in much shorter periods than previously considered possible. The lack of heat meters in this study meant that there were difficulties when attempting to model expected energy consumption; however, the observations made are important in any future studies. The use of Neural Network Analysis is also proving to be useful in the analysis of in-use data. Further research is being undertaken at Leeds Beckett University in this feild.

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EXECUTIVE SUMMARY

- This is the final report detailing the results of a 12 month energy monitoring research program at Stamford Brook, Altrincham. The report builds on fabric data from the initial project (Lowe, Bell and Roberts 2003) and subsequent research listed in the Stamford Brook references at the end of this document.
- Using energy consumption data from 84 dwellings along with information about their construction, thermal performance and household occupancy, the research investigated the relationships between energy consumption and the dwelling fabric, systems and occupants.
- The aim of the report was to identify what additional data collection was needed to explain patterns of energy consumption in buildings. The following three data collection methods enhanced the descriptive capacities of energy data, each being progressively more invasive:
    - Desktop surveys to establish ‘housing type’ sub categories to refine the data sets (number of bedrooms; whether they are terrace, mid terrace, semi detached or flats; construction type).
    - Remote questionnaires to gather data on occupancy and heating habits.
    - Post occupancy site visits to assess system commissioning and handover.
- Models of expected energy consumption were built using construction information collected from developers and the results of previous thermal performance testing. The models were refined using household information collected through self-administered questionnaires and data acquired from intensive monitoring undertaken on a subset of the dwellings. External weather conditions were monitored by a weather station installed at a college, adjacent to the site.
- Employing these methods increased accuracy when identifying unusual energy consumption. In addition, they often identified the causes of abnormal behaviour so that solutions could be sought. Without this additional contextualisation, inefficient energy consumption in a dwelling appeared normal (and visa versa) and may not have been identified through analysis of the energy data alone.
- The findings of this study could be significant, as smart metering becomes more widespread. Without additional contextual knowledge of the building’s fabric, its systems or occupants, approaches to educate and inform building occupants about energy consumption using only energy data derived from smart meters could lead to trends being overlooked or even misinterpreted. Future research may be useful to understand in more detail the scale to which each additional factor influences the predictive power of energy data.
- This has implications for predicting the payback rates of particular energy efficiency measures. Changes in energy use and efficiency can be better understood with historic energy use data and contextual information, without additional information homes are assumed to react homogenously which this report has shown is not the case and this may result in inaccurate estimation of the effectiveness of energy efficiency improvements.
- A large variation in weekly and annual gas and electricity consumption was identified across the monitored households; however, the interquartile range of consumption was relatively small. Comparison with other data sets indicated that the energy consumption of the households at Stamford Brook was favourable compared to similar new housing developments. Mean household electricity consumption was similar to an OFGEM

medium consumer and gas consumption was that of the OFGEM low consumer.

- Comparing individual household profiles against the development's average enabled a typical consumption to be identified; however, understanding the causes required additional contextual information, and it is important that this information is captured if useful feedback is to be provided to householders. Here, a typical consumption was understood by exploring questionnaire data, contact with the householder and site visits. In a number of cases, intervention measures were adopted, supporting other findings that monitoring energy consumption data can be used to affect consumption. In other cases, the consumption was the result of household circumstances and no intervention was necessary. If tools are to be developed which will enable the householder to understand their consumption; they will need to incorporate contextual information and building system performance.
- It was noted from the questionnaire responses and direct contact with the householders that some did not fully understand the systems within the home and their function. Householders have not been equipped with sufficient understanding to make the best decisions nor to diagnose problems when they occur. The system design, at the user/system interface has been found to present problems. If, homes are to be comfortable and perform efficiently, householders should be able to interact with the system to achieve the desired conditions.
- Parametric energy models explored the level of detail required to determine annual energy consumption. By using statistical descriptors of the participating households and thermal parameters from co-heating tests, a model of a typical household was developed. Using values that represented a, “typical dwelling”, energy consumption was predicted within 1 standard deviation of the mean. Models for individual dwellings gave predicted consumption, which varied from actual consumption by up to 47% using as-built parameters and no household details. Adding household information and internal monitoring data, the model's predicted consumption varied by up to 44%. This reflects the large variation in consumption observed in the energy monitoring.
- Parametric energy models were developed to derive dwelling heat loss parameters by back modelling from energy consumption and household data. The heat loss parameters derived from the co-heating tests undertaken previously were 1.2 - 1.4 W/m^{2}K. The average heat loss coefficient was 1.1 W/m^{2}K (st dev 0.1) using only energy data and 1.4 W/m^{2}K (st dev 0.2) incorporating monitoring data into the model. Indication that the models gave heat loss parameters in the range determined from coheating tests on similar dwellings. It is expected that similar methods could be used to determine performance of large groups of similarly constructed building stock. However, the band of uncertainty associated with such models will become increasingly problematic as the target performance becomes more stringent, and the difference between expected and actual consumption lessens. It is expected that more detailed energy use monitoring could increase the accuracy with which back modelling can derive heat loss parameters. Such options are possible where the efficiency of the heating system is known.

INTRODUCTION

1. Increased focus by the Government on minimising the impact of climate change by limiting the release of greenhouse gasses has led to both aspirational targets for reduction of carbon dioxide emissions and legislation. The Government's commitments include the Climate Change Act 2008 (DECC 2008) which binds the government to reducing greenhouse gas emissions through action in the UK and abroad by at least 26%, with respect to 1990 emissions, by 2020 and by 80% by 2050.
2. Energy use in housing accounts for approximately 30% of total final energy use in the UK and more than a quarter of carbon dioxide emissions (Kannan & Strachan 2009). In 2007, in order to tackle emissions from housing, the UK government announced that all new homes will be zero carbon from 2016 (CLG 2007).
3. While there is not a tradition of monitoring in the UK (Leaman *et al.* 2010); that which has been undertaken often records significant differences between the expected energy consumption of dwellings and the actual in-use consumption. The difference has typically been attributed to the behaviour of the householder. However, recent research indicates that the fabric of the houses and their systems do not achieve the performance expected at the design stage. For example, the dwellings tested at Stamford Brook, Altrincham indicated fabric performances approximately 20-25% below the design expectations. (Wingfield 2007) Similarly, the Sigma Home; built at the BRE Innovation Park as part of the Off Site 2007 exhibition, underwent a co-heating test and was found to perform 40% below the predicted performance at design stage (NBHC 2009; Stevenson & Rijal 2008), indicating that previous monitoring may be identifying poor total performance rather than the impact of household decisions.
4. Through the use of coheating tests and the observation of construction methods the magnitude and causes of fabric underperformance can be understood. However, undertaking co-heating tests on large numbers of houses would be time consuming and expensive, as such, a limited number of dwellings are tested and only a narrow view of dwelling performance is achieved. Identifying methods of assessing and understanding the performance of a larger number dwellings is required.
5. The Good Homes Alliance Standard (GHA 2010) now requires that dwellings are monitored for two years during initial occupation and the Technology Strategy Board have funded a number of monitoring projects through the Building Performance Evaluation funding (TSB 2010) and under Phase 2 of the Retrofit for the Future project (TSB 2011b). In addition, the introduction of smart meters, designed to provide the householder and energy suppliers with real-time data relating to the energy consumption; gas and electricity, within the home, will produce large data sets of energy consumption. Such data sets offer the construction industry in-use energy and environmental conditions data on a scale that has previously been unavailable. However, the understanding required to interpret the data to give dwelling performance is still being developed.
6. The research presented here examined energy consumption data from a large number of dwellings to explore the degree to which dwelling fabric performance could be distinguished from household behaviour. The results from a twelve month energy consumption monitoring programme are presented. Meter readings were collected from 84 dwellings at Stamford Brook, Altrincham. Additional household information and internal environmental data were collected from a subset of these dwellings.
7. By considering the typical energy consumption derived from a large number of dwellings, it was hoped to minimise the influence of individual household strategies towards achieving comfort and so gain a more informed, general picture of overall dwelling performance across the development.
8. By comparing individual dwelling consumption profiles with the typical consumption

across the development, a number of behaviours were identified which led to high energy consumption. The identification of these behaviours from the consumption data is discussed alongside possible methods for their prevention. To explore the impact of household behaviour, Leeds Met/UCL Parametric Domestic Energy models (Lowe *et al.* 2008) representing individual households, were developed using different levels of household detail. The predicted energy consumption was compared to the actual consumption and the possible causes of the discrepancy were considered

9. Ascertaining the degree to which the thermal performance of a dwelling can be understood from energy consumption data and how detailed the data gathered needs to be to give accurate results, will enable the construction industry to determine the real world thermal performance of buildings from in-use energy data. To explore this, back modelling was carried out using the Leeds Met/UCL Parametric Domestic Energy model (Lowe *et al.* 2008). Data gathered during the in-use monitoring period were input to the model, and values for individual dwelling heat loss parameters were collected and compared to heat loss parameter data gathered from previous testing on-site.

Stamford Brook development

10. The Stamford Brook development comprises approximately 700 cavity wall masonry dwellings, constructed by two national developers. At the commencement of the research approximately 400 of the dwellings had been completed and were occupied.

11. The Centre for the Built Environment research group at Leeds Metropolitan University was involved from the early stages of the project and assisted in the development of the building thermal performance specification within the comprehensive environmental performance standard (EPS) (Lowe *et al.* 2003). During the action research project, undertaken between 2001 and 2008, the team observed the construction of the development at critical stages of the fabric construction, and undertook post-completion testing of a selection of the dwellings.

12. The project identified a range of issues associated with standard construction methods that could impede the progress of new housing towards meeting more stringent energy consumption targets as they are introduced. Airtightness, envelope integrity and systems performance were among the areas, which require a new approach to repeatedly produce buildings of a high standard. On-site testing showed that the buildings were not produced consistently in line with design and that even when the construction details were effectively realised, the designed thermal performance values were not necessarily achieved (Wingfield 2008). The identification of the party wall bypass has led to a change in current regulations (HMG 2010) and highlights the importance of onsite measurement. Thermal bypasses occur where heat energy circulates around the insulation layer, via connecting gaps, cavities and thermal bridges that circumvent insulation or penetrate inadequately fitted barriers. The most striking finding from the work was the magnitude of the gap between energy and carbon performance, as expected at the design stage and that achieved in completed dwellings due to failings in the design and construction process. Realised energy consumption and carbon emissions, under standard occupancy, were around 20 to 25 per cent higher than design predictions.

13. A small scale intensive post-occupancy monitoring program was undertaken on four dwellings. The space heating energy consumption of the households were compared to the predicted consumption using a parametric domestic energy model. Using as-designed parameters, values of predicted and actual energy consumption for three of the four houses were similar; in one case, actual consumption was lower by about 5,000 kWh/a. However, as it had been shown that the design parameters were not accurate, adjustments were made to the models to represent the as-built conditions for each household. Changes were also made to reflect the household composition and was considered that the final models were more representative of the actual conditions.

As the models became more representative, the predicted and actual consumption values diverged before re-converging to within 500 – 600 kWh/a of each other. The modelling exercise reinforced the need to be able to describe the dwelling and the household in order to develop meaningful models.

Objectives of the research

14. This research extends the small scale monitoring undertaken during the previous research to a larger number of dwellings across the development. The main research aim is to investigate what factors can be disaggregated from various intensities of monitoring, what can be understood about the thermal performance of dwellings and their heating/hot water systems from energy consumption data alone and what additional information would be required to explain the patterns of consumption. In particular the investigation of how accurate back modelling using data gathered during the in-use monitoring period is when used to determine dwelling heat loss parameters.

METHOD

15. Construction information was collated from the developers and from the previous research. Weekly gas and electricity meter readings were collected from all participating dwellings. In addition, household, internal monitoring and pressure testing data were collected from a smaller number of households within the larger set.
16. The BRE Standard Assessment Procedure (BRE 2005) was used to model expected energy consumption. A series of models were produced to explore the level of detail relating to the dwelling and the household required to create representative models for the prediction of energy consumption. The following section outlines the data collection methods used during the project.

Data collection from developers

17. The developers were contacted and all available drawings describing construction and site layout, construction specification and SAP assessments, were obtained. Information relating to changes to the original specification was also obtained.

Energy consumption and household data collection

Invitation to householders

18. An information pack was hand delivered to approximately 400 occupied dwellings at Stamford Brook on the 5th March 2009 and again on the 31st March 2009. Eighty four households returned the consent form for energy monitoring; 15 households consented to taking part in the additional monitoring. The information pack is presented in Appendix A.

Meter readings

19. Energy consumption data were gathered by collecting electricity and gas meter readings on a weekly basis between 19th March 2009 and 2nd May 2010.
20. Two meter readers were recruited from the participating households. Requests for meter readers were sent out upon receipt of the initial permission form. The meter readers were employed through the university employment centre. The researchers collected the first weeks’ readings and then accompanied the meter readers for two visits. Postal plans of the site and a suggested route were provided to the meter readers.
21. The readings were recorded within Excel spread sheets and submitted to the research group following each data collection. The data were checked upon receipt before incorporating into the data set. At approximately 3 monthly intervals, the research team undertook the meter reading collection on-site as a secondary check, to ensure validity of the data submitted by the meter readers.
22. Meter readings collected from electricity meters were given in kilowatt hours (kWh), gas

meter readings were provided as gas consumption in cubic metres. Gas readings were converted to energy consumption by applying the regional calorific value of the gas supply (National Grid 2010). Daily calorific values for the Northwest region were obtained from the National Grid and an average value for March 2009, 39.6 MJ/m^3, was used to convert the volumetric meter readings to energy consumption values. All readings were normalised to give daily consumption.

23. Profiles of energy consumption using statistical descriptors of the data were produced to describe the general behaviour of the survey group throughout the year.

Questionnaire

24. A questionnaire was prepared by the research team to investigate householders' opinions of the performance of their house and their behaviour with respect to maintaining comfortable conditions in the home. The questionnaire was designed to be as short and simple as possible, while collecting all the necessary information relating to the number of people in the household and their occupancy patterns. The questionnaire is presented in Appendix B. The questionnaire was sent to households by post in August 2009. Of the 84 households participating, 62 (74%) returned their completed questionnaires. The data from the questionnaires were analysed using the SPSS 16.0 statistical software package (IBM 2007).

Internal monitoring

25. Internal environmental monitoring was undertaken to enable the description of actual conditions and identify any unusual conditions. Fifteen householders agreed to take part in the additional testing programme. Internal environmental conditions (temperature and relative humidity) were monitored at various positions in the dwelling using Gemini Data Loggers Tinytag sensors (TGU-4500). Details of the loggers are presented in Appendix E.

26. Sensors were installed in participating properties between 26th June 2009 and 31st October 2009. Households were invited to have either a combination of 3 temperature and humidity sensors and 1 carbon dioxide sensor or 1 temperature and humidity sensor. The monitoring was designed so that there would be one temperature and humidity sensor in each of the lounge, the kitchen and the master bedroom, and a carbon dioxide sensor in the lounge or master bedroom. This was achieved to varying degrees depending on availability of access in each household. Table 1 and Table 2 describe the monitored dwellings and the sensors installed and summarise the distribution of the sensors within the properties.

Table 1: House design, form and occupancy of intensively monitored dwellings.

House identifier	House design	House form	Occupancy
A1	Bespoke apartment	Ground floor apartment	2
A2	Avon	2.5 storey, semi-detached	2
A3	Chatsworth	2.5 storey, detached	3
A4	Derwent	2.5 storey, end terrace	2
A5	Derwent	2.5 storey, end terrace	4
A6	Derwent	2.5 storey, end terrace	2
A7	Derwent	2.5 storey, mid terrace	2
A8	Devoke	2.5 storey, semi-detached	2
A9	Devoke	2.5 storey, semi-detached	2

House identifier	House design	House form	Occupancy
A10	Devoke	2 storey, semi-detached	2
A11	Romsey	2 storey, detached	3
A12	Romsey	2 storey, detached	3
A13	Wye	3 storey, end terrace	1
A14	Wye	3 storey, end terrace	1
A15	XT2	2.5 storey, semi-detached	2

Table 2: Distribution of sensors by room types.

House identifier	Location of temperature and humidity sensors			Location of carbon dioxide sensor
A1	Master bedroom	Open plan lounge and kitchen	Spare bedroom/Study	Master bedroom
A2	Kitchen	--	--	--
A3	Master bedroom	Lounge	Kitchen	Lounge
A4	Lounge	Kitchen	Master bedroom	Lounge
A5	Lounge	Child’s bedroom	Master bedroom	Child’s bedroom
A6	Lounge	Kitchen	Master bedroom	--
A7	Lounge	Kitchen	Master bedroom	Master bedroom
A8	Lounge	Kitchen	Master bedroom	Master bedroom
A9	Lounge	Kitchen	Master bedroom	Master bedroom
A10	Lounge	--	--	--
A11	Lounge	Kitchen	Master bedroom	Lounge
A12	Lounge	--	--	--
A13	Lounge	Kitchen	Master bedroom	Master bedroom
A14	Lounge	--	--	--
A15	Lounge	Kitchen	Master bedroom	Kitchen

Pressurisation testing

27. Ventilation is an essential consideration when addressing a building’s thermal performance because in “leaky” dwellings, uncontrolled ventilation may lead to excess heat loss as escaping heated air is replaced by incoming colder external air. However, sufficient fresh air is required by the household to remove smells, stale air etc. The building fabric of the dwellings at Stamford Brook had a target air permeability of 5 $m^3/(h.m^2)$ @ 50Pa and were installed with mechanical ventilation systems to ensure adequate ventilation (either Mechanical Extract Ventilation (MEV) or Balanced Mechanical Ventilation with Heat Recovery (MVHR)).

28. Households, taking part in the additional testing, were requested to allow dwelling pressurisation tests of their home. Eleven pressurisation tests were completed in accordance with the standard methods used for building regulations compliance (ATTMA 2007), except that both pressurisation and depressurisation tests were completed and the mean of the two reported as the test result.

29. In the historical research, pressurisation tests were completed on 31 individual dwellings; the results are presented in Appendix D. Three of those dwellings tested were among the suite of dwellings participating in the additional monitoring. This allowed the comparison of air permeability results between the point of completion by

the developers and following a period of occupation by householders.

Weather data

30. External weather conditions strongly affect the heat balance of a dwelling. Solar gains contribute heat which can lower total space heating demand during the heating season but can also lead to overheating during the non-heating season. Wind effects produce pressure differences between inside and outside, and across the dwelling which, in turn, creates air movement through and out of the building and within cavities. External temperatures affect the direction of conductive heat flow to or from the building with both wind speed and moisture content of the air affecting the rate of heat transfer.

Weather station

31. A weather station measuring external temperature, relative humidity, average wind speed and vertical south-facing solar insolation was installed at Trafford College, adjacent to the main entrance to the Stamford Brook housing development. Data from the station were recorded at 10 minute intervals and downloaded weekly via GSM modem. The readings were checked for data integrity and stored on an database.

Meteorological office data

32. Weather data were obtained from the Meteorological Office for their site at Woodford air field, National Grid Ref: 53°20′20.4″ N, 2° 9′ 21.6″ W, 15 km from the development. Six months of data were obtained between October 2009 and March 2010. The daily data comprised maximum, minimum and mean air temperature; mean wind speed, max (gusts) speed and wind direction, solar radiation, number of hours of sunshine and the amount of rainfall and snow fall.

Local data

33. Eleven days of on-site weather data were lost during processing between 2nd and 12th of April 2010, this was replaced by data taken from the “Weather underground” website (www.wunderground.com 2010), a repository for local weather data from amateur weather data collectors. The nearest local weather station was IMANCHES1, Lat 53.5 N Lon 2.3W, Salford, Manchester. Data from the Wunderground website are not verified and are not for commercial use.

Degree day data

34. Degree day data are a time based measurement of the temperature difference between external temperature and an internal base temperature and are frequently used during the monitoring of energy consumption for heating and cooling in buildings. Data published by the Carbon Trust uses a base temperature, of 15.5ºC. The base temperature is the external temperature at which a notional dwelling requires no additional heating to achieve the desired internal temperature. The actual base temperature varies between dwellings and depends on the mean temperature of the internal space, the internal gains, solar gains and the heat loss coefficient of the building.

35. Degree day data were calculated using the on-site weather station data using a base temperature of 15.5°C to enable comparison with other data sets using the same base temperature. Additional degree day values were calculated for modelling within the Leeds Met/UCL Parametric Domestic Energy Model (Lowe *et al.* 2008) using base temperatures derived by the model.

36. Degree day data are published by the Carbon Trust for 18 regions in the UK. Data was collected for the monitoring period. Stamford Brook is located in the West Pennines region (Carbon Trust 2011).

Parametric Domestic Energy Modelling

Intensive monitoring: Annual energy models

37. Parametric energy models are not able to capture all of the factors which influence household energy consumption and, as such, there will always be a difference between the model's prediction and actual consumption values. Individual dwellings' models can be improved by collecting detailed information about the household through interviews and monitoring the internal environment in order to make adjustments to the model. Alternatively, by using large data sets, comprising many dwellings, it is expected that the influence of individual decisions are minimised and that the behaviour tends towards a norm which can be assumed and a single model, describing these conditions, is developed. Modelling was undertaken using both of these methods.
38. The Leeds Met/UCL Parametric Domestic Energy Model (Lowe *et al.* 2008) was used to develop models of household energy consumption. Three models were developed with increasing detail, described as Level 1, 2 and 3. The data used in each model are described in the paragraphs below and summarised in Table 3.

LEVEL 1: As-designed construction

39. The as-designed assessment used the fabric design parameters (U-values, thermal bridging, air-tightness, and boiler efficiency) as specified in the design documentation for the dwellings. Dwelling measurements: floor area, width, depth and room height, and window areas, were taken from design construction drawings supplied by the developers. House type, location (number of sheltered sides) and orientation were taken from the site layout (hand-annotated copy of drawing ref PA-NT-PA1). No adjustments were made to occupancy or internal environmental conditions, instead the standard assumptions in the model were used.

LEVEL 2: As-built construction

40. The observation of building methods and historical testing indicated that the thermal performance did not always meet the design specification. In order to account for the difference between the design and the built performance, revised as-built thermal parameters were developed from observations, testing and modelling results undertaken during the previous research at Stamford Brook. These as-built parameters were applied to the Level 2 models.
41. Pressurisation tests were undertaken on 11 of the dwellings and the results were included within the as-built assessment where available. If test results were not available, then the average result from pressurisation tests, undertaken during the previous research, was used.
42. The number of heating degree days were calculated for each model using the average daily temperature obtained from the on-site weather station at Stamford Brook.

LEVEL 3: Household data

43. Level 3 models replaced the assumed values describing the household with measured data. Values for occupancy, electricity consumption and internal temperature were adjusted to match the data that were gathered during the monitoring period.

Table 3: Information used within each level of parametric domestic energy models.

Level 1	Level 2	Level 3
Fabric design parameters Site layout Construction details	As-built parameters Site layout Construction details Pressure test results Degree day data	As-built parameters Site layout Construction details Pressure test results Degree day data Occupancy Electricity consumption Internal temperature monitoring

Typical Stamford Brook household

44. Statistical analysis of energy consumption and household characteristics enabled the description of a typical dwelling and household to be developed. The bimodal distribution of floor area, shown in Figure 1, led to two models being developed, for a two storey, 75 m2 gross floor area (GFA) dwelling and a three storey, 145 m2 GFA dwelling. Two models were developed for each dwelling, one using as-designed thermal parameters and another using the as-built thermal parameters developed during the previous research project.

Back modelling

45. With energy performance and efficiency standards for new buildings becoming more exhaustive under current and future building regulations, the construction industry increasingly need to demonstrate that buildings will perform to the standards required of them. Traditionally this is done through time and resource intensive testing, such as pressure testing and coheating testing; in order to determine the energy performance of the building as built.

46. Due to the time and resource intensive nature of current testing methods it is not practical to undertake such testing on a large scale, such as a housing development, meaning only a selection of representative buildings are tested in such circumstances. The construction industry is in need of a method of assessing whether buildings performed to the standards they have been designed to. This need could be met through the use of back modelling using in-use energy monitoring; potentially giving a value for thermal performance using energy consumption data and internal temperature data.

47. Rather than using the Leeds Met/UCL parametric domestic energy model to predict the energy consumption of the dwellings, back modelling was undertaken to estimate a value for the total heat loss through the fabric (heat loss coefficient of the building). This was then used to calculate a value for the dwelling's heat loss parameter. Data used in the back modelling includes: electricity consumption, air leakage, hot water consumption, mean internal temperature and occupancy data.

48. The known values for energy consumption were used within the model; the value for the dwelling's heat loss coefficient was then adjusted within the model to produce a value for dwellings space heating demand that came within 10% of the actual space heating demand (acquired from the monitoring period). The value for the heat loss coefficient was then recorded, and divided by the dwelling's overall floor area to provide a heat loss parameter. Using this method the heat loss parameter can be estimated with much less intensive methods than traditionally used

49. The use of heat loss parameters to quantify the thermal performance of dwellings allows the thermal performance of different dwellings to be compared, regardless of variations in size. A heat loss parameter cannot identify specific failings in a building's fabric, though it can indicate the presence of faults for further investigation.

RESULTS

Dwelling types and layout

50. Households from approximately four hundred dwellings were invited to participate in the research project of which eighty-four households agreed to take part in the energy monitoring research.

Layout of scheme

51. The development was constructed in three phases, of which dwellings from phases 1 and 2 were complete at the time of the research. Dwellings were present as terraces, detached and semi-detached houses and a number of apartment blocks. The layout of the Stamford Brook development was designed to maximise the benefit from passive solar gains to the properties.

52. The dwelling orientation and the number of sheltered sides for each dwelling's energy model were taken from the site layout drawing (hand annotated copy of drawing: ref PA-NT-PA1).

Dwelling types

53. Fifteen apartments participated in the research, ten of which were of bespoke design, located within the landmark buildings at the entrance to the site. Seventy-two houses participated, comprising twenty-five different design types. The house types with the greatest number of participating properties were the Chatsworth and Derwent. The Chatsworth is a three bedroomed house constructed as detached, semi-detached and terrace forms. The Derwent is a three bedroomed house constructed as semi-detached and terraced forms. House types and forms of the participating dwellings are presented in Appendix C.

Description of sample: Internal layout

54. Construction dimensions and building layouts were obtained from construction drawings provided by the developers. This data together with window dimensions, number of storeys and orientation were required inputs for the Leeds/UCL parametric domestic energy model.

55. The apartments were all one-storey dwellings, while the houses were two to three storeys with a number having room-in-roof constructions. The dwellings had between two and five bedrooms with gross floor areas in the range 58 m^2 – 189 m^2. The distribution of floor areas of the dwellings is presented in Figure 1. This distribution shows a bimodal form, with the first mode centred at 70 - <80 m^2 and the second centred at 130 - <140 m^2.

56. The previous research at Stamford Brook showed that some design features, such as the juliet balcony, bay window and room-in-roof knee voids had specific issues relating to in-situ thermal performance. These issues were a result of difficulties associated with the construction of the features on-site or were intrinsic to the design.

Fabric and system performance parameters

57. Forty-four pressurisation tests were carried out on completed dwellings during the initial Stamford Brook trial. The average air permeability was 4.5 $m^3/(h.m^2)$ @ 50Pa (st dev. 1.7) with 68% achieving the design target of below 5 $m^3/(h.m^2)$ @ 50Pa. Six co-heating

tests were undertaken. The results of the tests plus modelling of thermal junctions led to the development of revised thermal parameters to describe the performance of the completed dwellings. These as-built parameters **are presented in Table 4**

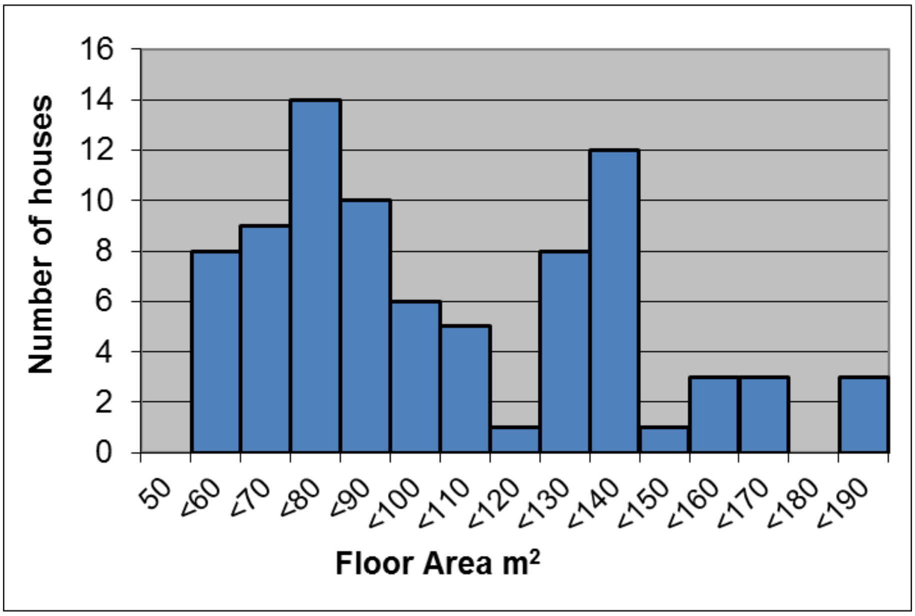

Figure 1: Distribution of floor area of dwellings in the research sample. n=84

Table 4: Comparison of As-designed and As-built parameters.

	As-Designed	As-Built Estimated
Floor U-value (W/m^{2}K)	0.172	0.172
Wall U-value (W/m^{2}K)	0.23	0.25
Roof U-value (W/m^{2}K)	0.142	0.142
Window/Door U-value (W/m^{2}K)	1.3	1.3
Total Linear Thermal Bridging ΔU (W/m^{2}K)	0.03	0.06
Party Wall U-value (W/m^{2}K)	0	0.5
SEDBUK Boiler Efficiency (%)	91.3	85
Air Permeability (m^3/(h.m^2) @ 50Pa)	5	4.5
Glazing Ratio	0.20	0.20

Pressurisation tests

58. Pressurisation tests were undertaken on 11 of the dwellings participating in the additional monitoring. The pressure test data are given in Table 5 and summarised alongside the previous test results in Table 6. All pressurisation test results are presented in Appendix D.

59. Air permeability results were in the range 3.7 -10.5 m^3/(h.m^2) @ 50Pa with a mean value of 6.7 m^3/(h.m^2) @ 50Pa. Only two of the tested dwellings achieved the design target of below 5m^3/(h.m^2) @ 50Pa. One dwelling had a test result of 10.5 m^3/(h.m^2) @ 50Pa which is above the current regulatory target of 10 m^3/(h.m^2) @ 50Pa.

60. Pressurisation testing was undertaken on A10 after the construction of the conservatory; however, it is expected that airtightness may have been poorly affected by the construction, which will have interrupted the air barrier.

61. Three houses had been tested during previous investigations. Two properties had very similar air tightness results indicating that little or no degradation of the fabric had

occurred during its occupation. In the third property, air leakage had increased by 32% since initial testing; the cause of the increase was not identified as no assessment of air leakage pathways was undertaken. Increased leakage could be due to deterioration of the air barrier, such as cracks produced by general settlement of the dwelling, or as a result of the building being occupied, such as degraded window and door seals or additional penetrations to the fabric for wiring to external lights or aerials.

Table 5: Pressurisation test results.

House identifier		House type			Pressure test m^3/(h.m^2) @ 50Pa	Date undertaken	Historical pressure test result m^3/(h.m^2) @ 50Pa	Date undertaken
		Storey	Bed rooms	Form				
A1	APT	apartment			6.01	08/10/09	--	
A2	DER	2.5	3	semi-detached	3.72	07/04/10	--	
A4	DER	2.5	3	end terrace	6.83	10/06/09	4.64	04/05/05
A5	DER	2.5	3	end terrace	7.3	17/06/09	--	
A6	DER	2.5	3	end terrace	10.54	17/06/09	--	
A8	DEV	2	3	end terrace	5.87	07/04/10	--	
A9	DEV	2	3	end terrace	8.08	17/06/09	--	
A10	DEV	2	3	end terrace	8.5	12/05/10	-	
Tested following the addition of a conservatory. [*]								
A11	ROM	2	4	detached	6.08	12/05/10	6.08	05/04/06
A13	WYE	3	3	end terrace	4.71	06/10/09	4.64	21/11/05
A15	XT2	2.5	3	end terrace	6.27	02/06/10	--	
All dwellings					6.72			

Table 6: Summary of all pressurisation test data at Stamford Brook.

Dwelling form	Mean pressure test m^3/(h.m^2) @ 50Pa	Standard deviation	Number of dwellings[†]
Apartment	4.5	2.2	4
2-storey, detached	4.1	1.8	17

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[*] The dwelling was tested without doors separating the conservatory from the dwelling because the householder intended to use the conservatory in this manner. The additional surface area of the conservatory was added to the dwelling surface area for the calculation of the air permeability.

[†] Where the air permeability test has been repeated during this research, the original result has been used.

2 ½ -storey, detached	7.1	1.9	11
3 storey end terrace	5.3	0.7	7
All dwellings	**5.3**	**2.0**	**39**

62. The more recent tests have higher leakage rates than those undertaken during the previous research which has led to an increase in the mean value across the development. Previously, differences in performance between the dwelling forms were identified; the 2.5 storey dwelling had higher leakage rates than the other forms. With the inclusion of the additional data, no particular form can be identified as performing differently, as shown in Figure 2.

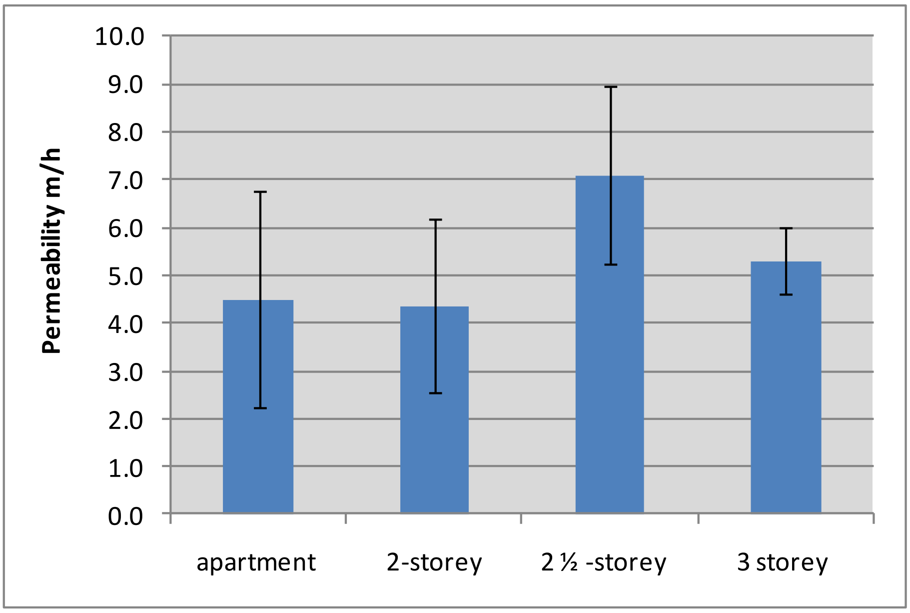


Figure 2: All pressurisation test data, including results from Wingfield (2008)

Household data

63. Household data were gathered though a self-administered questionnaire. 73% of the households participating in the energy consumption research completed and returned the questionnaire. The main results of the questionnaire are presented in the progress report dated November 2009 (Sutton and Bell 2010). A number of the key points are summarised here.

64. The most frequent household occupancy (41%) is two adults without children; 28% of the dwellings have at least one child. 86% of the households are occupied by three or less persons. The average household size was 2.2 persons. The distribution of occupancy is shown in Figure 3.

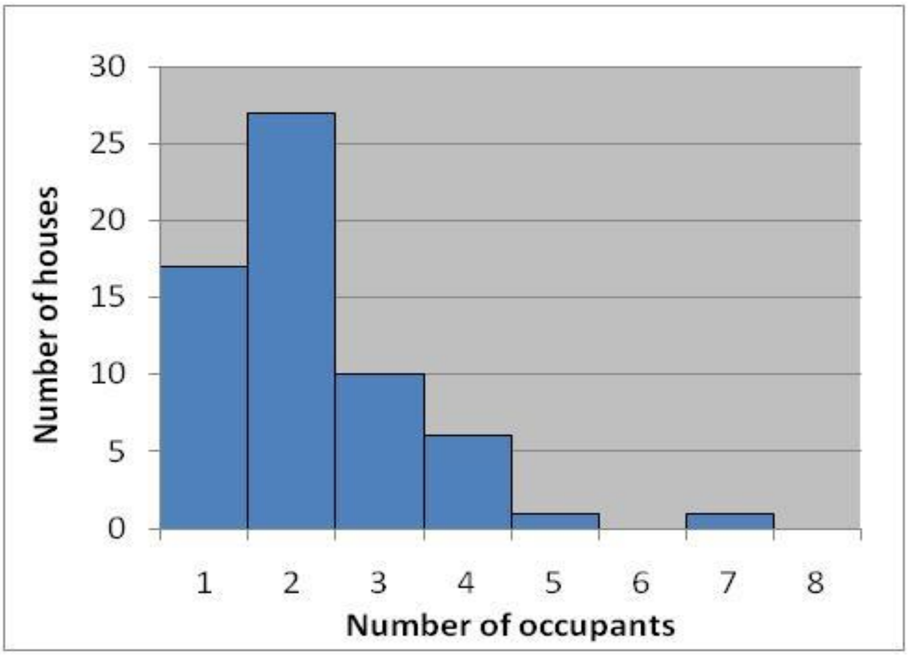


Figure 3: Distribution of occupancy.

65. 63% of the households are unoccupied during the daytime and all householders indicated that they stayed in the property at weekends.

66. The majority of householders indicated they they found their houses thermally comfortable throughout the year. In general, households used a combination of methods to maintain comfort but most households used window opening during the summer and adjusting the central heating system during the winter. 46% of householders indicated that they open windows during the winter to control temperatures. Reasons why owners opened windows were not obtained; however, opening windows will increase the rate of fresh air exchange, or householders may find it difficult to achieve the correct temperature using the household thermostat or TRVs.

Household data

Energy consumption

67. Electricity and gas readings were collected weekly from each participating dwelling between March 2009 and May 2010. Gas meter readings were available for all but two dwellings, which had meters in locked back garden areas. Electricity readings were available on a weekly basis for all but two houses, which had meters in back garden areas with locked access, and for 10 apartments for which meters were inside locked cupboard areas. Two of these householders provided readings; one apartment householder provided weekly readings which they had been collecting for two years. Another apartment householder provided readings irregularly.

68. Gas meter readings were collected as volumes and were converted to energy consumption by applying the calorific value factor, available from the National Grid. All readings were adjusted using the average of the first month’s (March 2009) calorific value data (39.6 MJ/m^3). The calorific value data were subsequently reviewed throughout the monitoring period to ensure that large variations from the chosen value

were not unaccounted for. Calorific values between March 2009 and April 2010 were 38.6 - 40.4 MJ/m^3 with an average of 39.4 MJ/m^3.

Weekly energy consumption

69. Daily gas consumption, calculated from the weekly data, was in the range of 0.31 – 130 kWh/day, with the interquartile range using between 5 and 20 kWh/day, as shown in Figure 4.
70. During the non-heating season, (May to September) gas consumption provides hot water and cooking the mean consumption during the non-heating season, is approximately 10 kWh/day. During the heating season the interquartile range increases to between 30 and 75 kWh/day. The total range is much greater also, between 0.31 and 134 kWh/day.
71. Dwellings which had the maximum consumption on a weekly basis were considered. Six houses had the maximum gas consumption for at least a week over the year, although one dwelling outweighs the rest. The dwelling which had the maximum weekly consumption most frequently (30 of 52 weeks) had the highest occupancy (7 adults) of all participating dwellings. Its hot water demand was determined to account for 56% of its total gas consumption over the year and the household's electricity consumption was second highest of all dwellings.

Figure 5 presents mean electricity consumption patterns over the period April 2009 to March 2010. Most of the houses have consumption in the range 5 to 16 kWh/day across the year. During the non-heating season, mean consumption is stable with most consumption occurring within a narrow range. As the monitoring period passes into the heating season, mean electricity consumption is found to increase and the range of consumption increases. Five dwellings had a maximum consumption values over the course of the monitoring. One household had very high consumption for much of the period (22 weeks) caused by the householder using the immersion heater to provide hot water. This was identified by the researchers, the householder was informed and the problem was rectified. The household which had the highest consumption for the remaining weeks also had the maximum gas consumption and had a high occupancy.

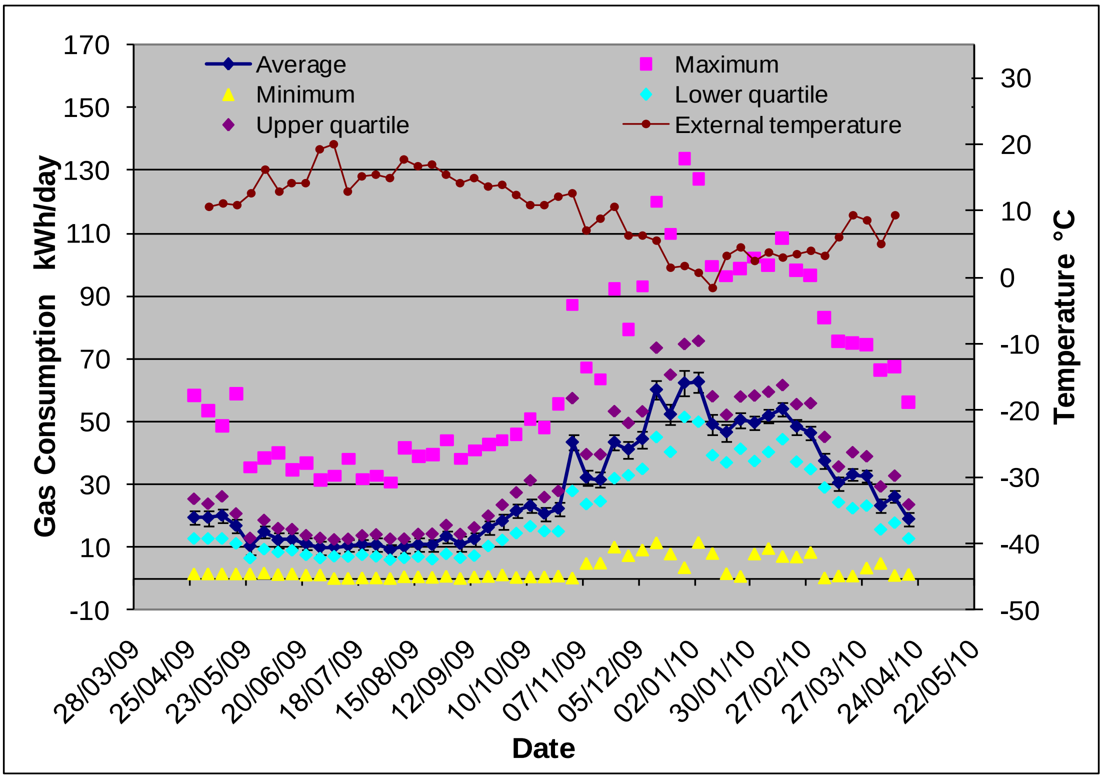


Figure 5: Weekly gas consumption. n=82

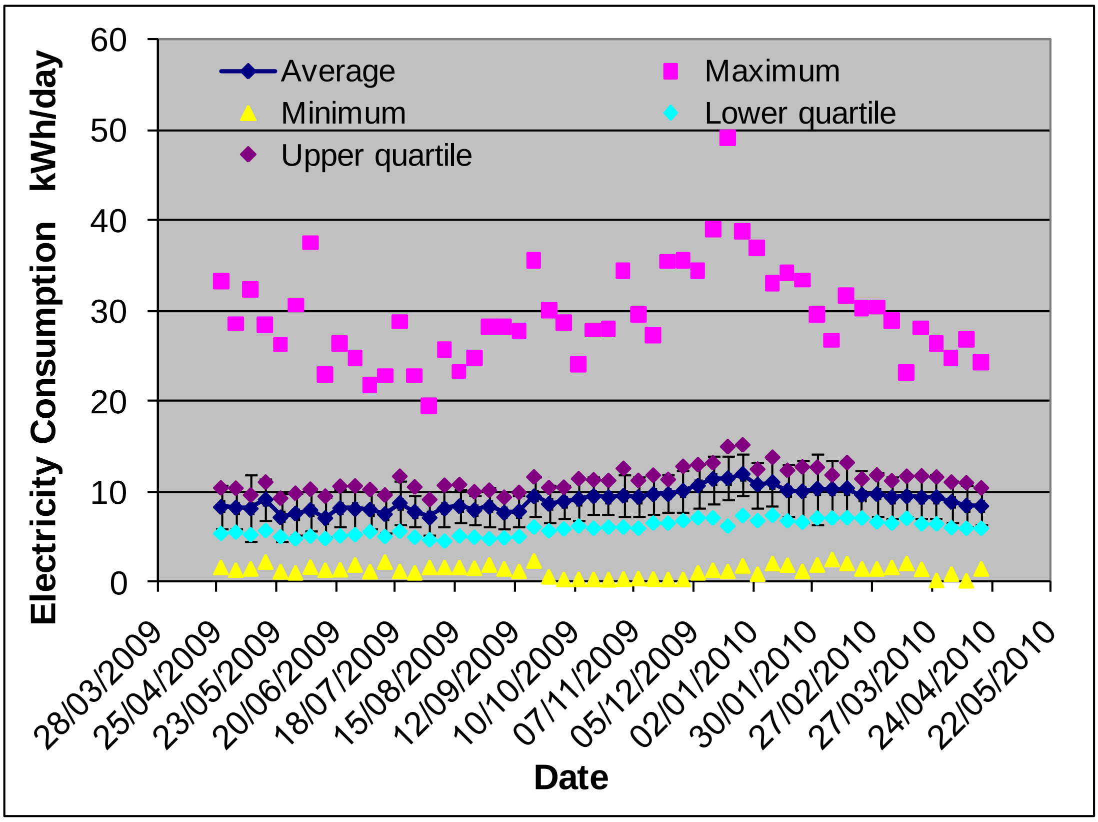


Figure 4: Weekly mean electricity consumption n=72

Annual energy consumption

72. Total annual energy consumption for each household was calculated using data between 27th April 2009 and 26th April 2010. The distribution of total energy consumption is shown in

73. Table **7** and shows a normal distribution; the mean value (14,140 kWh/a) is slightly higher than the modal range 10,000 - 12,500 kWh/a, affected by the highest consuming dwellings. The highest consuming household (Cliveden), is an outlier with respect to the normal distribution, this is attributed to the high occupancy (7 persons); the mean occupancy is 2.2 persons. The upper quartile of dwellings consume twice the amount of energy as the lower quartile**.**

Table 7: Summary of annual energy consumption

	Electricity kWh/a	**Gas kWh/a**	**Annual Energy Use kWh/a**
Number in sample	72	82	71
Maximum	9,573	21,958	31,532
Minimum	667	2,417	6,548
Mean	3,371	10,357	14,140
Standard deviation	1,606	3,798	4,428
…as a percentage of the mean	47.6%	36.7%	31.3%

74. The broad range of energy consumption across the dwellings was expected given the observed range of house sizes and occupancy. A small number of dwellings had consumption outlying the normal range, described by two standard deviations from the mean. The distribution of gas consumption is shown in Figure 6. One dwelling has gas consumption outside of the normal range. The distribution of electricity consumption is shown in Figure 7; two dwellings have electricity consumption outside the normal range**.**

Figure 6: Distribution of annual gas consumption.

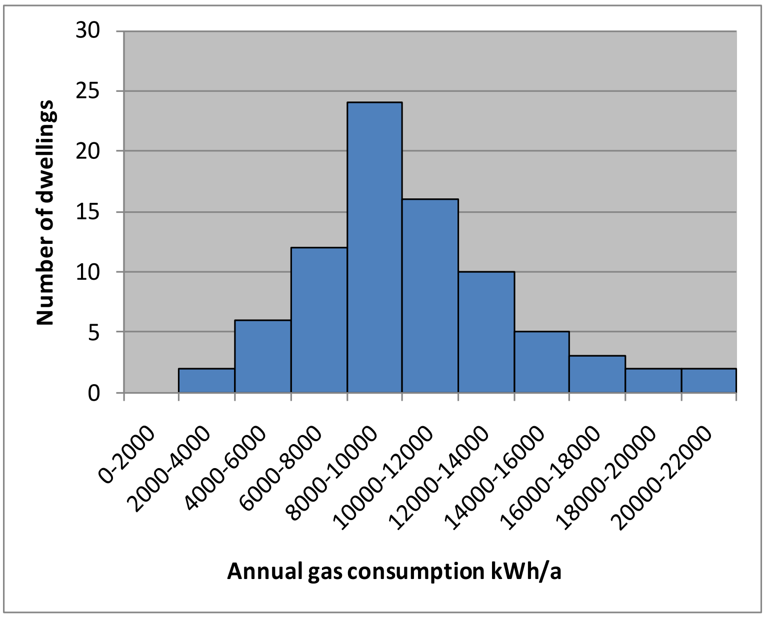
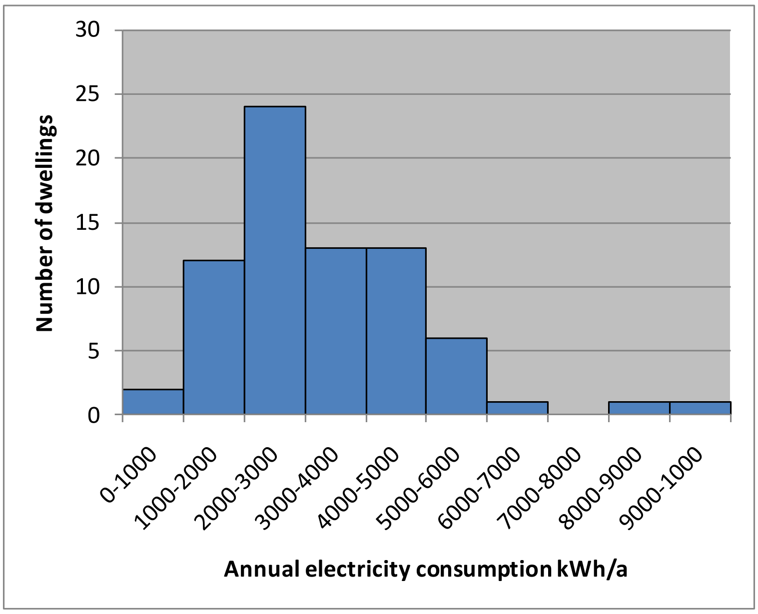


Figure 7: Distribution of annual electricity consumption.



75. One household was an outlier for both gas and electricity, with an occupancy of seven; the household was the largest within the participating dwellings. However, when normalised to floor area it was in the normal range. The second household with electricity consumption outlying the normal range was unknowingly using the immersion to supply hot water. When the total energy consumption and space heating consumption were normalised for floor area, none of the dwellings were outliers to the normal range.

76. Energy in the home is used to meet a variety of needs, lighting and appliances, cooking, hot water and space heating. Summer gas consumption was extrapolated to give annual hot water and cooking demand. Annual space heating demand was then calculated as the difference between total consumption and hot water and cooking demand.

Table 8: Quartile ranges of total energy consumption.

77.	**Total energy**		
	kWh/a		
	Value	Range	% of total energy consumption
1st quartile	11,202	n/a,	17.1%
2nd quartile	13,229	2,027	22.0%
3rd quartile	16,009	2,780	24.8%
4th quartile	31,531	15,522	36.1%

Table 9: Quartile ranges of electricity and gas consumption.

	Electricity			Gas		
	kWh/a			kWh/a		
	Value	Range	% of development's total consumption	Value	Range	% of development's total
1st quartile	2222	1555	13.6	8423	6006	15.3
2nd quartile	2964	742	19.9	9943	1521	21.6
3rd quartile	4132	1168	25.9	12238	2295	25.7
4th quartile	9574	5442	40.6	21958	9719	37.4

78. Figure 8 shows the distribution of energy demands between space heating, hot water, cooking, electrical appliances and lighting. Electricity consumption accounted for between 6.9% and 63.1% (average 23.7%) of the total household energy demand. Hot water and cooking accounted for between 1.9% and 53.5%, with an average 29.2%. The remaining energy consumption provided space heating accounting between 15.4% and 70.0% (average 47.1%). Consumption of the same amount of energy by gas and electricity leads to different amount of carbon dioxide being released. Carbon dioxide emission factors used in this report were taken from SAP 2009 (BRE 2010). The emission factor for gas was reported as 0.198 $kgCO_{2eq}/kWh$ and 0.517 $kgCO_2/kWh$ for grid electricity. The distribution of carbon dioxide emissions across the site is shown in

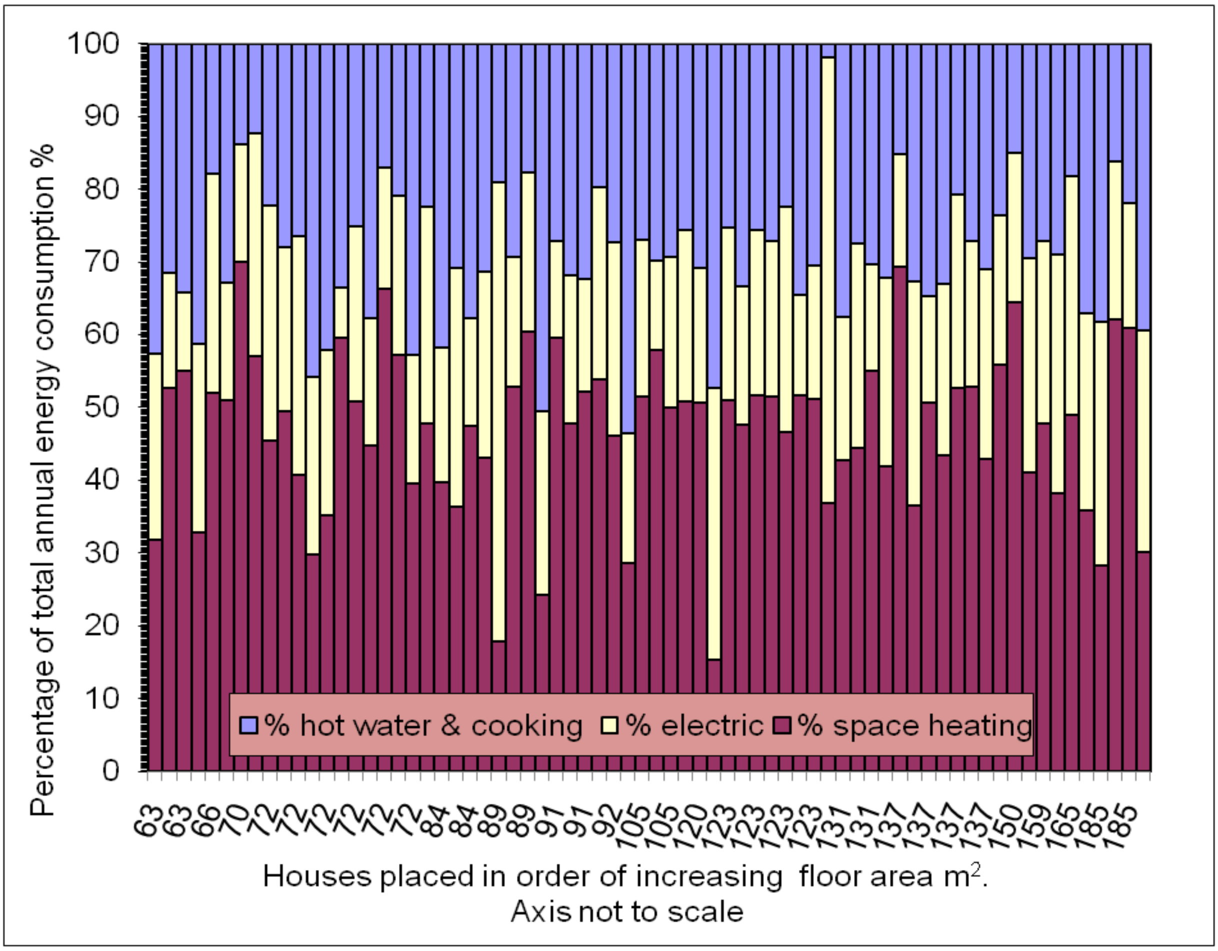


Figure 8: Distribution of energy demand per household

Figure 9.

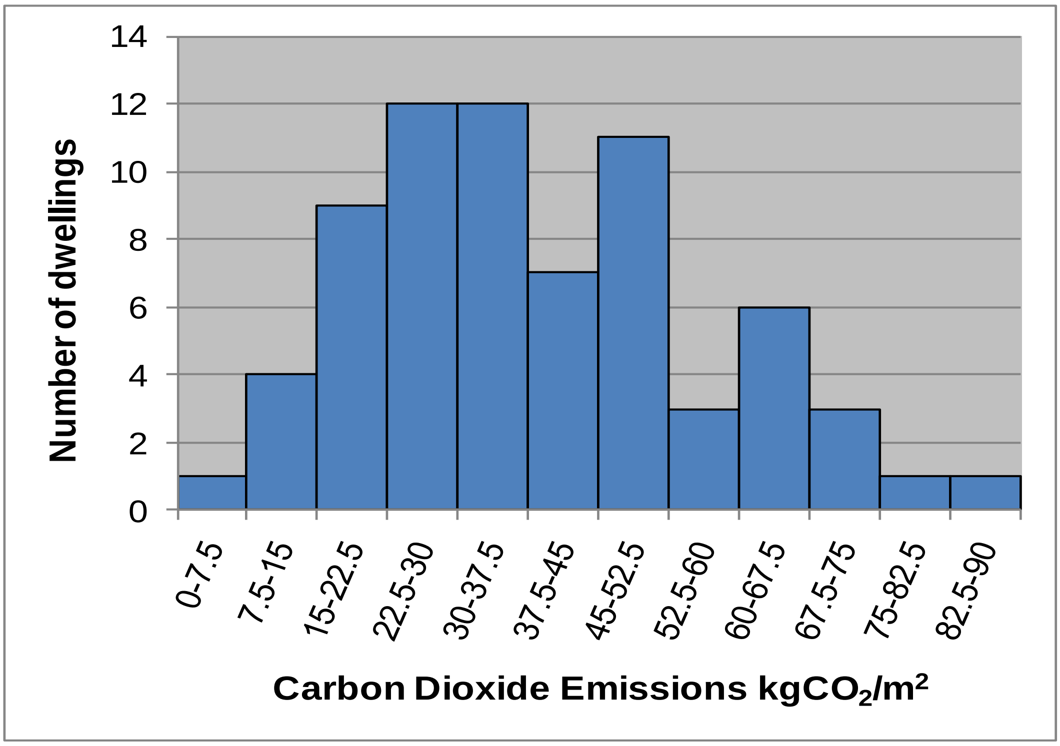


Figure 9: Distribution of carbon dioxide emissions associated with energy use.

Normalised space heating

79. Figure 10 shows there is a large range of values in the distribution of normalised space heating demand. Mean normalised space heating demand is 63.5kWh/m^2/a higher than the modal range 50-60kWh/m^2/a

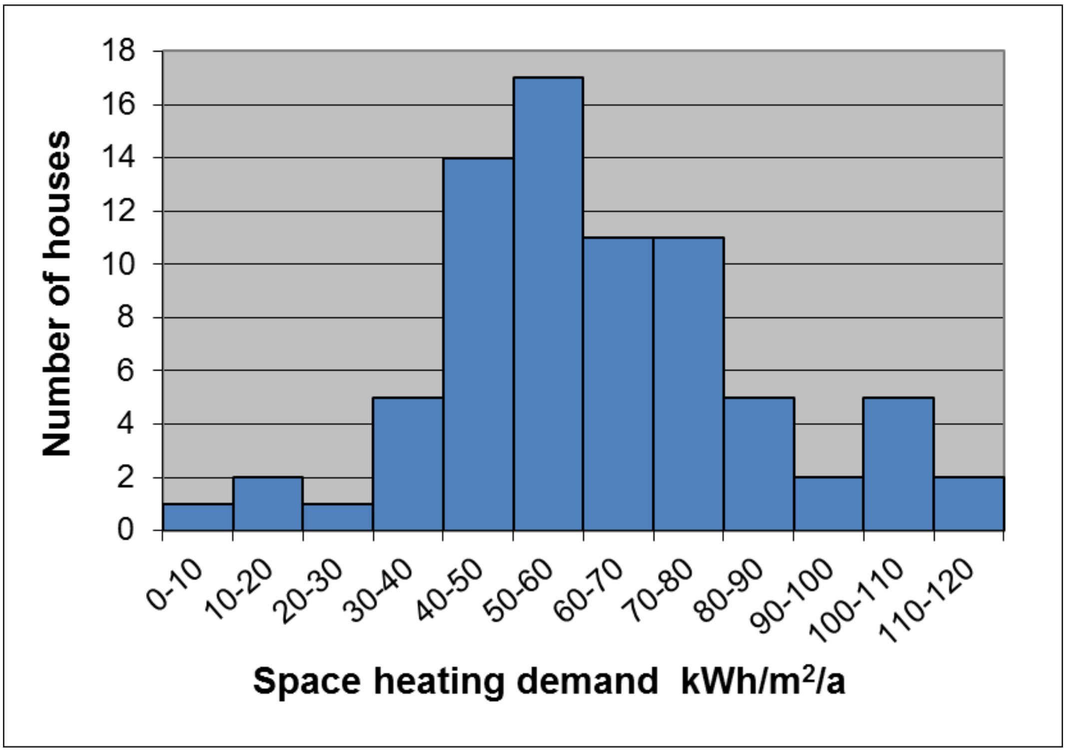


Figure 10: Distribution of normalised space heating demand.

Normalised energy consumption

80. The range of dwelling size and the number of occupants across the monitored dwellings has been described above. Relationships between floor area and total energy consumption, electricity consumption, and space heating were explored, the strength of the correlations are shown in Table 10; no statistically significant relationships were identified.

Table 10: Relationship between energy consumption and house parameters.

Relationship	**r^2**
Floor area *vs.* total energy	0.33
Floor area *vs.* space heating	0.17
Floor area *vs.* annual electricity	0.21
Occupancy *vs.* total energy	0.01
Occupancy *vs.* hot water demand and cooking	0.02
Occupancy *vs.* annual electricity	0.01

GROUPING OF ANALYSES

81. Dwellings were grouped by form (detached, semi-detached, end terrace, mid-terrace and apartment) and by number of storeys (1 storey, 2 storey, 2.5 storey with a room-in-roof and 3 storey); the space heating demand for each of the groups was compared. Graphs of average weekly values for each are shown in Figure 11 and Figure 12.

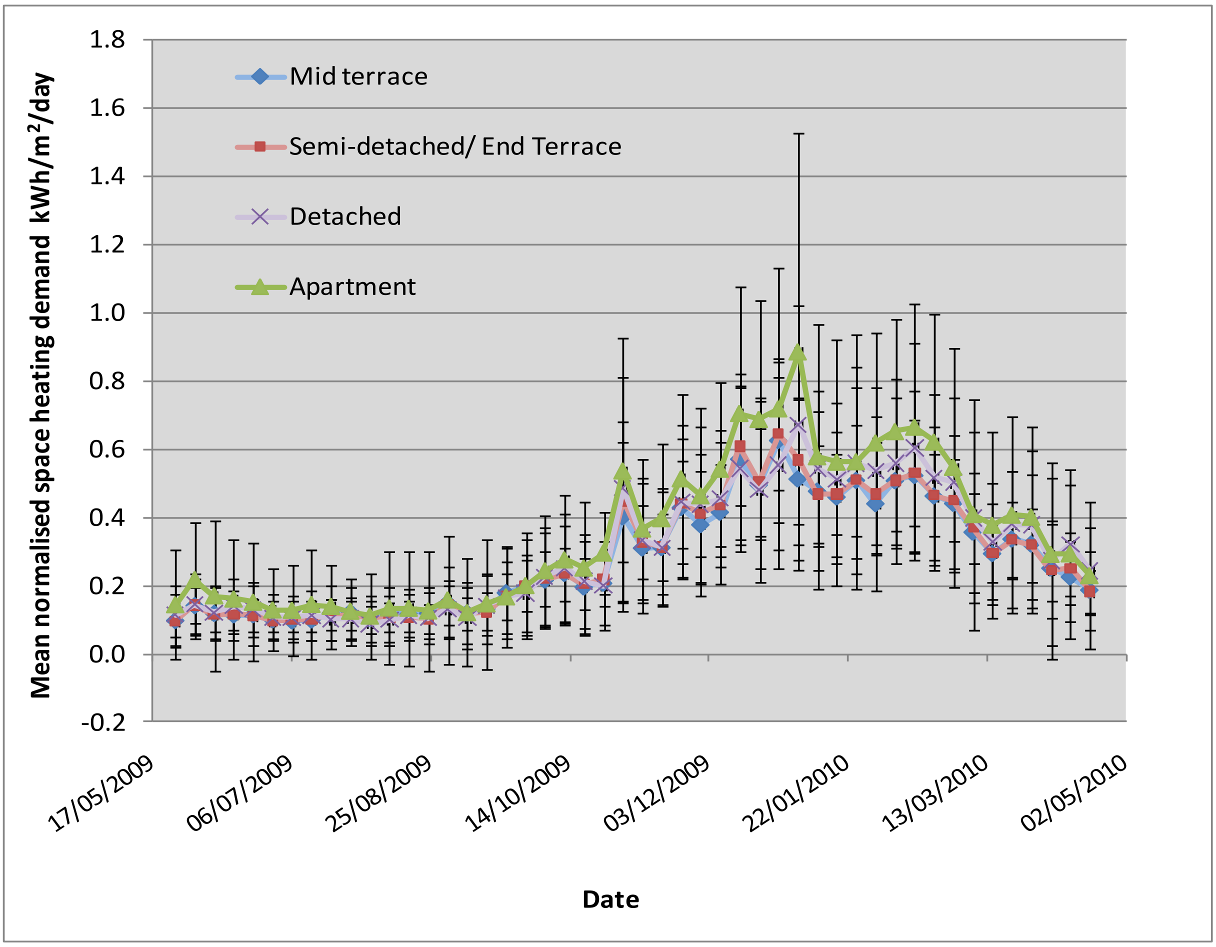


Figure 11: Comparison of space heating demand for different dwelling forms.

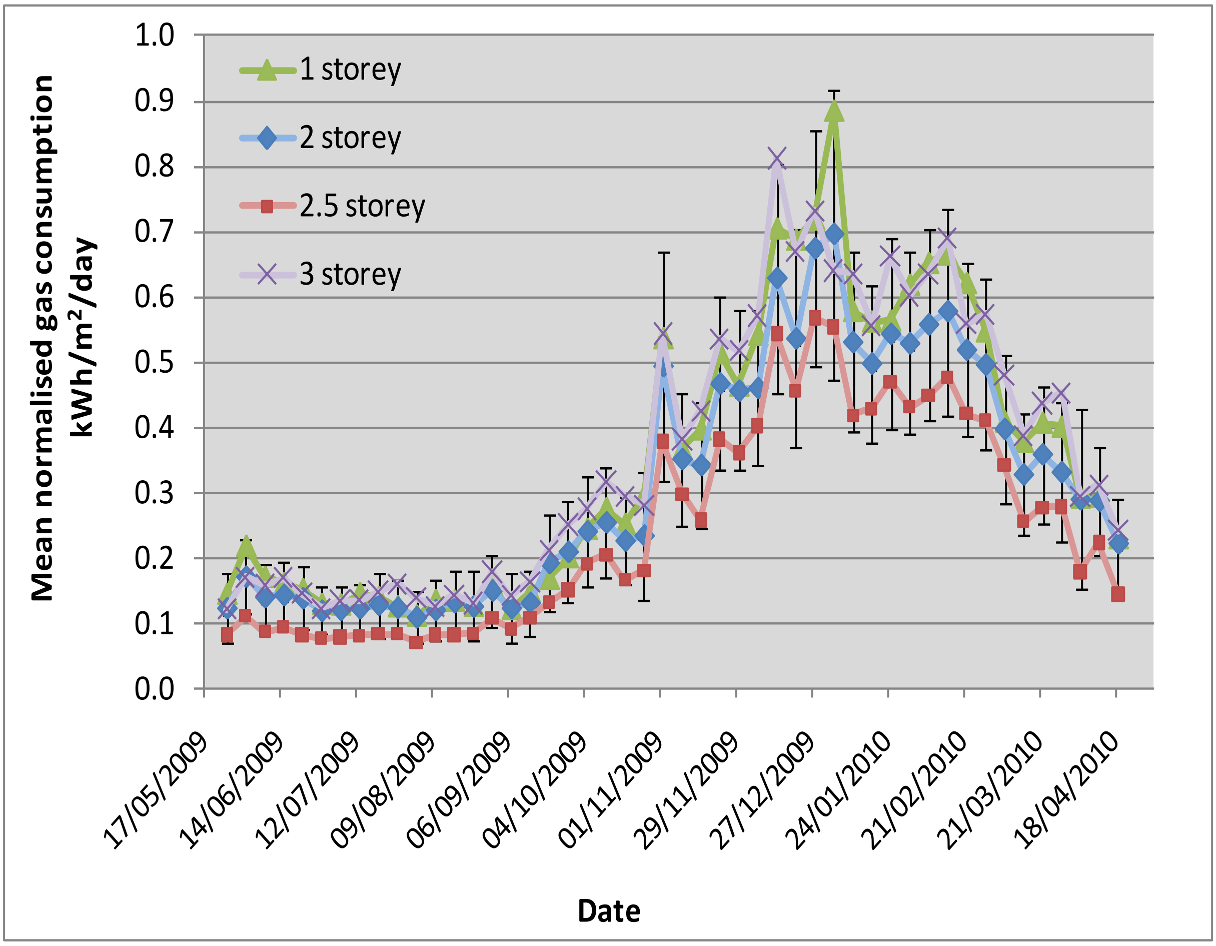


Figure 12: Comparison of space heating demand for dwelling with different numbers of floors.

ANALYSIS OF INDIVIDUAL PROFILES

82. Individual dwelling consumption patterns enable the impact of a household's decisions to be seen. By understanding the factors which result in the observed consumption curves it is possible to identify key actions which influence household behaviour. During the monitoring period, unusual energy consumption patterns were identified within individual household profiles. A number of these are described below to demonstrate that it is possible to discern patterns in energy data and relate these to specific issues. If households are to gain the most benefit from smart meters then any interface between the data collector and the user needs to have the capacity to learn typical usage patterns and identify any divergence from these.

Changing the Dwelling Fabric

83. Household A10, a participant in the intensive monitoring, built a conservatory onto their dwelling in November 2009, during the monitoring period. The conservatory adjoined the living room. It was understood that the purpose of the conservatory was to increase the living area and it was expected that the doors separating the lounge and conservatory would be frequently left open or possibly removed. The conservatory fabric had a lower thermal performance (Higher U-value) than the original dwelling fabric, therefore reducing the overall dwelling efficiency if the area was used and heated during the heating season. As such, it was expected that space heating would increase.

84. The monitoring undertaken following completion of the building work indicated that the householder adopted new behaviours which further impacted on their energy consumption. Figure 13 shows gas and electricity consumption for all houses of the Devoke type, before and after the construction of the conservatory. The graph shows that gas and electricity consumption in A10 was similar to that of other dwellings of a similar dwelling type prior to the construction of the conservatory in November 2009. Following the works, the electricity consumption increased and resembled the gas consumption curve more closely; responding to external temperature. Through contact with the householder, it was established that an electric heater was used in the conservatory over winter. The increased use of conservatories during the heating season has been explored elsewhere (Oreszczyn 1993). Smart meter data would potentially be able to inform the householder of this significant change in consumption at an early stage, however, advice from the conservatory manufacturers could have been more appropriate for minimising the impact. Awareness of the energy consumption associated with heating the conservatory may lead to reduced use during the winter months. Alternatively, the addition of a radiator connected to the central heating system would lead to an increase in gas demand but lower carbon dioxide emissions and lower costs than heating with electricity.

Hot water system failure

85. During the monitoring, two households were identified with very high electricity consumption relative to their gas consumption. On investigation, it was found that both households had the isolation switch of their hot water storage cylinder immersion heaters turned on continuously and were unaware of it. This led to the immersion heater maintaining the water temperature in the cylinder at 60°C (the default setting for the immersion heater thermostat) 24 hours per day. Electricity is both more carbon intensive and of greater cost per unit of energy than gas, resulting in greater CO_2 emissions and capital costs than using gas to heat water.

86. Household A5 approached the research team near to the beginning of the monitoring period to express concerns that their electricity consumption was very high. They reported that they had spoken to their electricity supplier who had informed them that their consumption was typical. Monitoring indicated that the household's electricity consumption was high when compared to other properties of the same design and to the development as a whole, but would still be within the overall variation. Gas consumption was identified as lower than typical for the type of household.

87. It was agreed with the householder of A5 to undertake additional investigation. It was quickly identified from a walk-round survey that the hot water tank immersion heater was turned on. The householder reported that it had been left on continuously since they moved into the property because they had been told not to switch it off during the initial house induction.

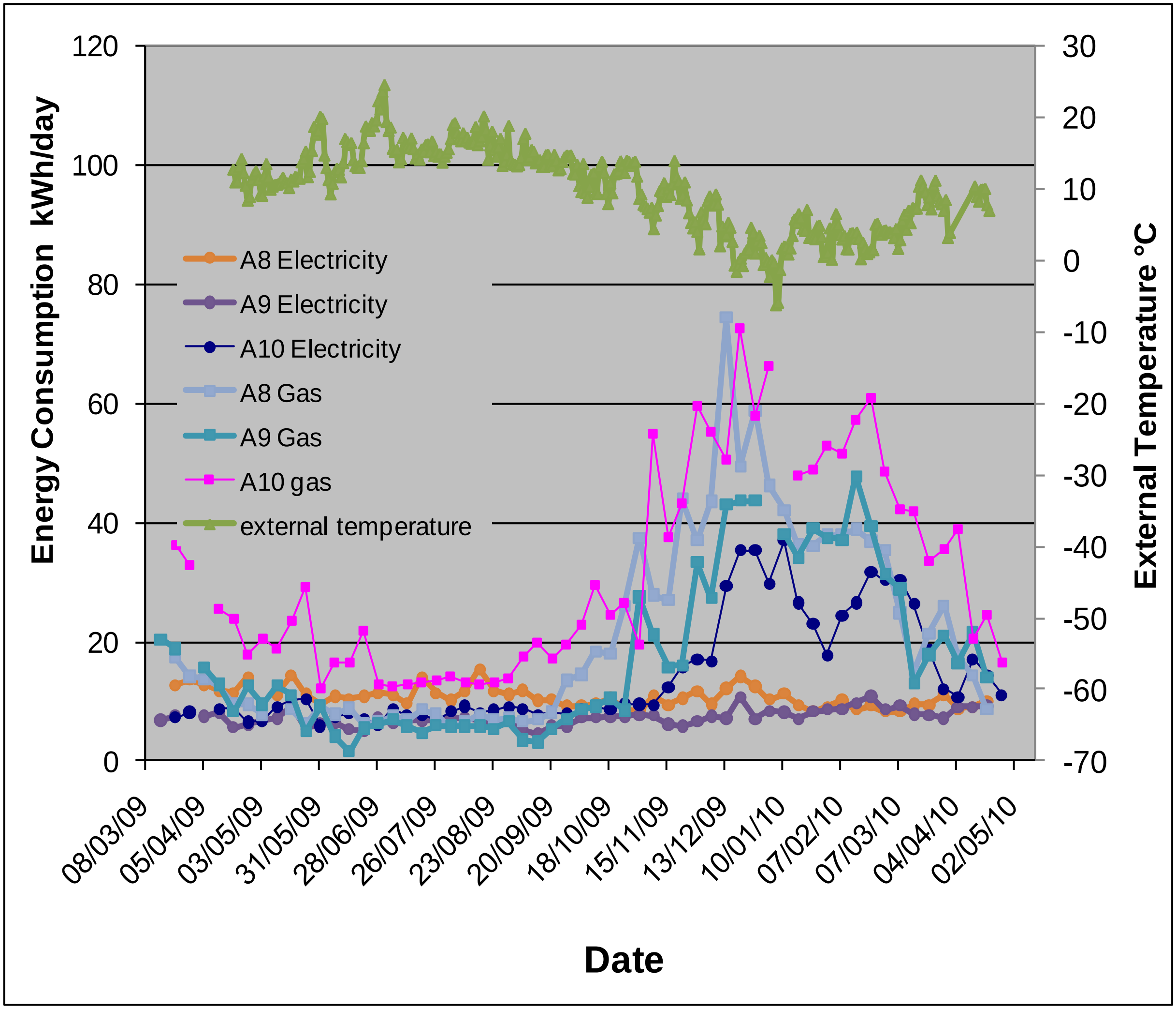
88. After the immersion heater was switched off, it transpired that it had been the only source of hot water to the house because the heating system had been installed incorrectly and was not able to supply hot water heated by the gas boiler. The developers were contacted and the boiler problem was rectified. Following the intervention the household's energy consumption became more typical as shown in Figure 14.

89. It is feasible that the confusion occurred because the control switches for both the ventilation system and the immersion heater are located in the same cupboard (in these 2 dwellings) and are unlabelled. Instructions to leave the ventilation system operating may have been mistaken as advice to leave the immersion turned on. More clear advice to the householder at handover and labelling of the switches would enable the householder to have better control over the systems in the dwelling.

90. The use of the immersion heater instead of the gas boiler to produce hot water had an

effect on carbon emissions as well as financial implications. The standard carbon emission coefficients in SAP2009 indicate that electricity in the UK produces 0.517 kg CO_2/kWh and gas produces 0.198 CO_2kg/kWh; as such, using electricity to heat water would account for greater carbon dioxide emissions than producing the same amount of hot water with a gas boiler.

Figure 13: Comparison of energy consumption for Devoke dwellings.



91. By comparing the consumption of household A11 with that of another household within the same house type (A12), the impact of the use of the immersion heater can be assessed. Both households had similar occupancy patterns, but House A12 had an additional child of school age. Table 11 shows that the total energy consumption and how it is consumed in the two dwellings are very different. Household A11 consumes

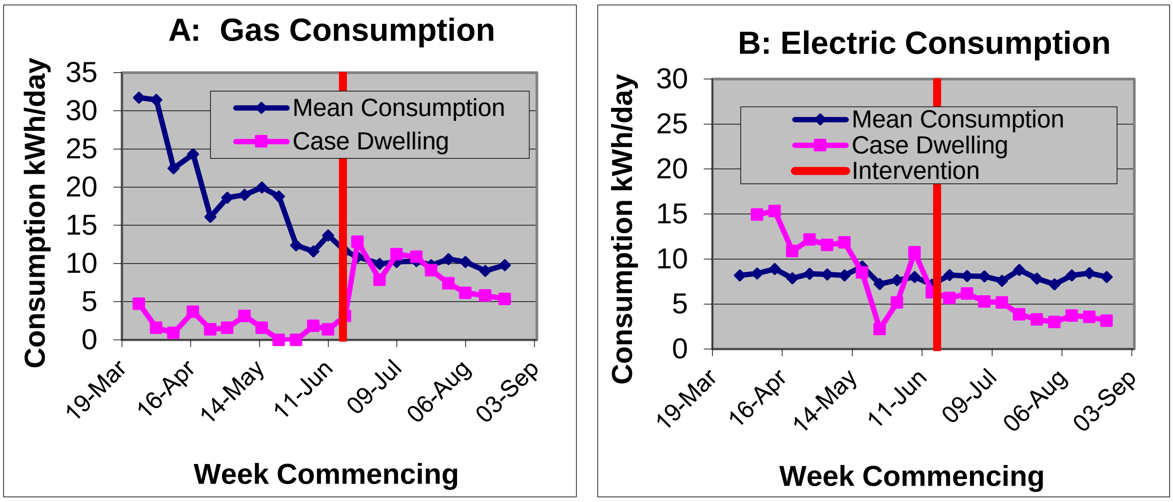


Figure 14: Gas and electricity consumption before and after intervention in dwelling A5.

more electrical energy than gas while House A12 has much greater gas consumption. By attributing an estimated 3,500 kWh of the electrical demand to the supply of hot water, then the additional carbon dioxide impact of using the immersion rather than the boiler is 1,050 $kgCO_2$.

Table 11: Comparison of energy consumption within Romsey type dwellings

	Annual electric kWh	Annual Gas	Space heating	Gas for hot water and cooking	Total Energy
House A11 ROM	8,837	5,601	5,330	2,710	14,437
House A12 ROM	3,415	13,905	7,414	6,491	17,320
Difference	5,422	-8,304	2,084	-3,781	-2,883

92. In this case, the problem was identified and resolved early in the monitoring and the effects of using the immersion are not seen within the annual data. However, in the household A11 the problem was not identified until December 2009, after 9 months of monitoring had been completed. Previous monitoring of this household by the research team confirmed that the immersion heater was not previously used to produce hot water.

Occupancy Patterns

93. One householder indicated, within their questionnaire, that they lived abroad during the winter. It was expected that this would lead to lower total energy consumption due to reduced space heating demand during the winter. However, their total gas consumption (10,309kWh) was close to the average value and the space heating (6,479KWh) was above average.

94. The householder recorded that while they are abroad their thermostat is set to 15.5ºC. The householder did not indicate the timings which were used to heat the property during the winter months. If the heating was on for long periods or continuously then household temperatures similar to occupied dwellings would be expected and the dwelling would be considered to perform similarly to other dwellings on the development. However, if the timer was set to come on for short periods throughout the day then the dwelling appears to be performing poorly. These issues highlight that in some cases a significant amount of detail is required to interpret energy consumption data.

Electrical Heating

95. Household A16 had the lowest total energy consumption of all participating households of which the electricity consumption is a high proportion (63%). The dwelling is occupied by one person who indicated within the questionnaire that they used an electric heater to supplement their heating, which was used for 30 minutes each day. The reasons for the householder using an electric heater for heating are not understood. The householder may feel that by using an electric heater in one room is more efficient and cheaper than using the central heating system. However, by adjusting the thermostatic radiator valves (TRVs) in each room to the desired temperature in order to only heat occupied rooms, more efficient use of energy and reduced carbon emissions could potentially be achieved.

96. When compared with dwellings of similar construction type, it can be seen that while the total energy consumption for house A16 is low, they have a large carbon dioxide impact because the electricity has a greater impact per unit of energy than gas consumption, as shown in Table 12.

97. **Table 12: Comparison of energy consumption and carbon dioxide impact within Fyne type dwellings.**

	Annual electricity kWh	Annual gas kWh	Space heating kWh	Total Energy kWh	Total CO_2 $kgCO_2$
House A16 Fyne	4,132	2,417	1,172	6,548	3,145
House A18 Fyne	2,733	9,710	7,522	12,443	4,440
House A19 Fyne	1,527	7,027	4,523	8,554	2,947

Internal environmental conditions

Household temperatures

98. Tinytag sensors measuring temperature and relative humidity were installed in 15 properties; 11 houses had 3 sensors each and 4 other properties had 1 sensor each. Data were downloaded to Tinytag Explorer software and exported to Access and Excel for processing.

99. Figure 15 and Figure 16 show daily average temperature profiles for 2 of the monitored houses. Figure 15 shows data for a dwelling in which the lounge temperatures are higher than the kitchen and bedroom during the heating season. In contrast, in Figure 16 lounge temperatures were lower than those in the other rooms. The ranges of actual daily mean internal temperature between houses are shown in Figure 17. The range of mean daily temperatures across the monitored dwelling is largest during the heating season with a maximum range of 8.3ºC occurring in December. These differences in mean temperature may be influenced by the difference in the dwellings' thermal performance, how households manage comfort within them; the temperature at which the householder is comfortable, and the occupancy level. The dwelling with the highest mean temperature is occupied throughout the day and is kept warm for medical reasons.

100. Most households' mean internal temperatures fall between August and December then rise again towards the beginning of the non-heating season. This suggests that people adapt how they achieve comfort when external conditions are coldest not by maintaining the internal temperature of their homes through increasing the levels of heating, but by other measures such as wearing additional layers of clothing or accepting lower levels of thermal comfort. Using a mean internal temperature; taken over the whole of the heating season, does not take this into account and would likely lead to an over-estimate of the space heating required.

Table 13: Summary of household temperatures.

101. House code	Number of sensors	Mean daily temp (heating season) °C	Reported thermostat setting: from questionnaire °C	Recorded peak temperature in any individual room °C
A1	3	22.1	22	32.7
A2	1	18.9	22	22.9
A3	1	19.6	21	32.9
A4	3	18.4	22	29.1
A5	3	17.1	26	30.9
A6	3	19.8	20	34.5
A7	3	19.1	18	32.4
A8	3	20.2	20	29.3
A9	3	18.6	20	29.5
A10	1	20.4	20	32.4
A11	3	17.0	20.5	28.8
A12	1	19.0	22	22.3
A13	3	19.3	20	27.9
A14	1	18.8	21	31.0
A15	3	15.5	21	29.0

102. The previous research at Stamford Brook suggested that the dwellings could be prone to overheating when temperatures rose above 30°C on successive days (Wingfield et al. 2008); the householders in the three storey dwellings in particular had previously identified overheating as a problem. Several householders commented within the questionnaire that rooms were sometimes too warm during the summer. Where rooms were identified, they were described as upstairs bedrooms. Peak measured temperatures were in the range 22.3 to 32.9°C and are recorded in Table 13. However, none of the sensors recorded sustained high temperatures over a number of days. A2 and A12 appear to have low peak temperatures; however A2 was located in the kitchen and as such the temperature is not considered particularly low. The sensor in A12 is located in the lounge and as such the peak and mean temperatures are considered low; However the sensor was positioned on the floor, in the corner of the room; as required by the householder, as such the temperature may not be representative of the room temperature, but indicate a cold spot.

Degree day data

103. The following sources of degree day data were gathered for comparison with data from the on-site weather station:

- The SAP assessment method provides an annual degree day value and offers data for base temperatures at 0.5° increments between 1.0 - 20.0°C. The values are derived from a 20 year rolling average.

- The Carbon Trust provides degree day data based local weather data, with the United Kingdom divided into 18 regions.
- Daily mean temperature data were also obtained from the Meteorological Office data, for Woodford airfield (NGR: 3898E - 3824N), for a period of six months between October 2009 and March 2010.
- Data were lost from the on-site weather station between 2nd and 12th April, replacement data were obtained from the Wunderground website.

104. The degree day data, using a 15.5°C base temperature, presented in Table 14, illustrates the variation between values available for the site. The Carbon Trust dataset is freely available, but has a large regional applicability; it indicated a higher number of degree days than the on-site weather station for every month of the year. Annual values for degree days between April 2009 and March 2010 taken from Carbon Trust data are greater than as indicated by the on-site weather station data. This leads to an over estimation of the space heating required. For the Meteorological Office data, the number of degree days for each month was typically found to lie between those calculated for the on-site weather station and those by the Carbon Trust. The total degree days value obtained using the Met Office data does not include temperature data for the period April to September, and consequently is not a direct comparison with the other data sets, which include data from outside of the main heating season.

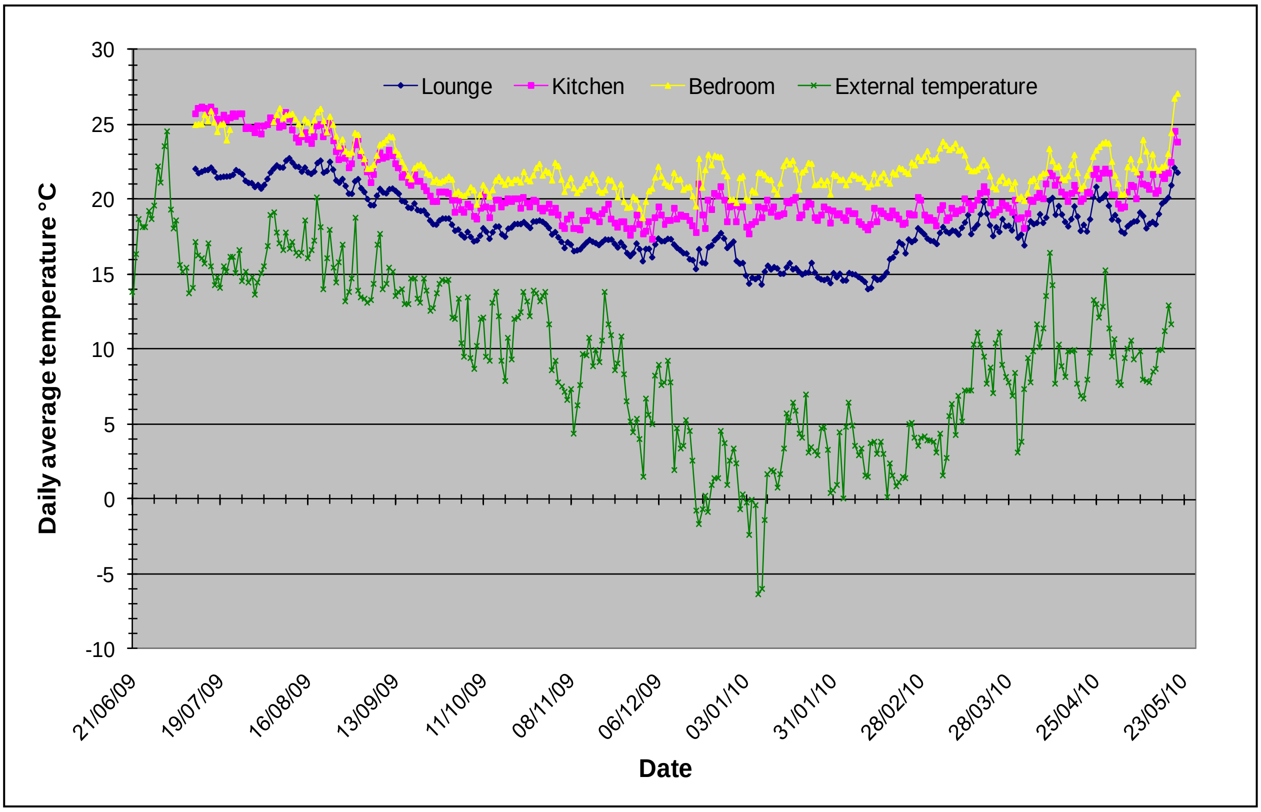


Figure 15: Mean daily internal temperatures; A5

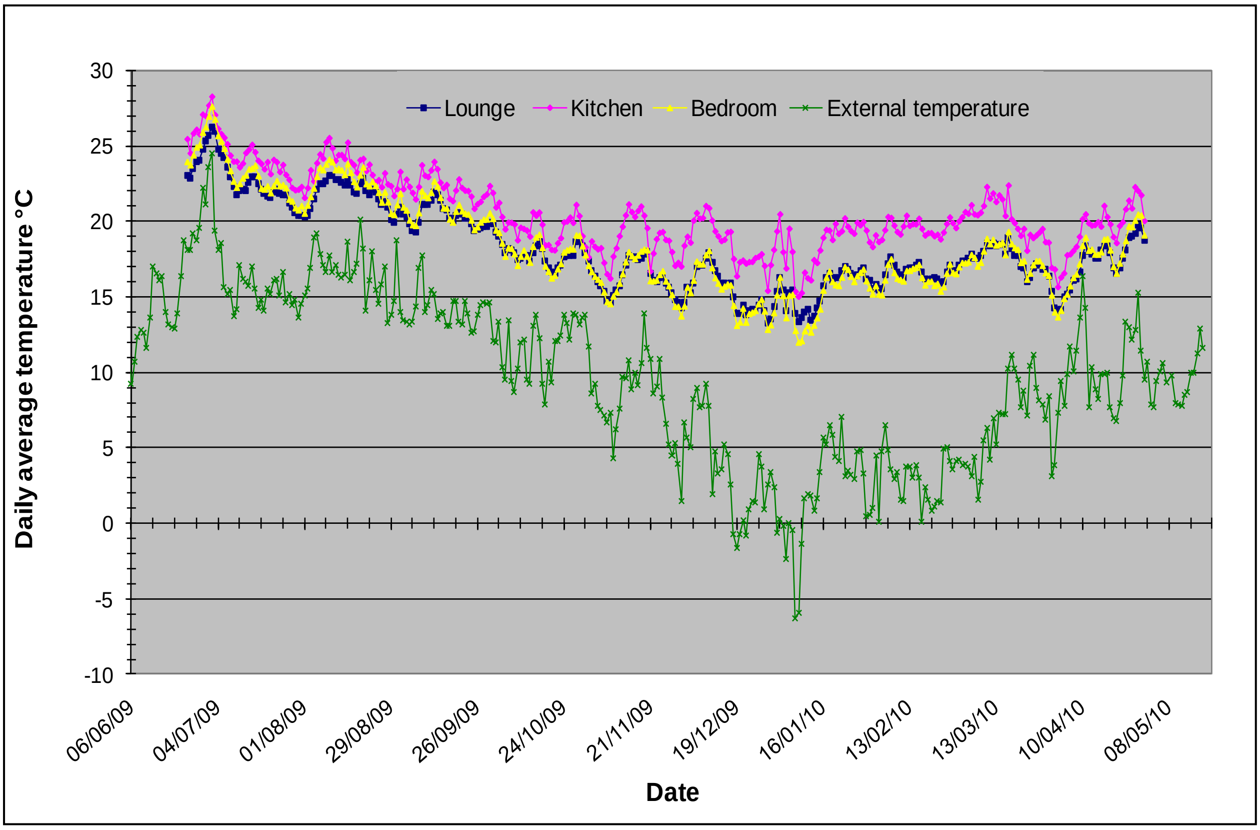


Figure 16: Mean daily internal temperatures, A8.

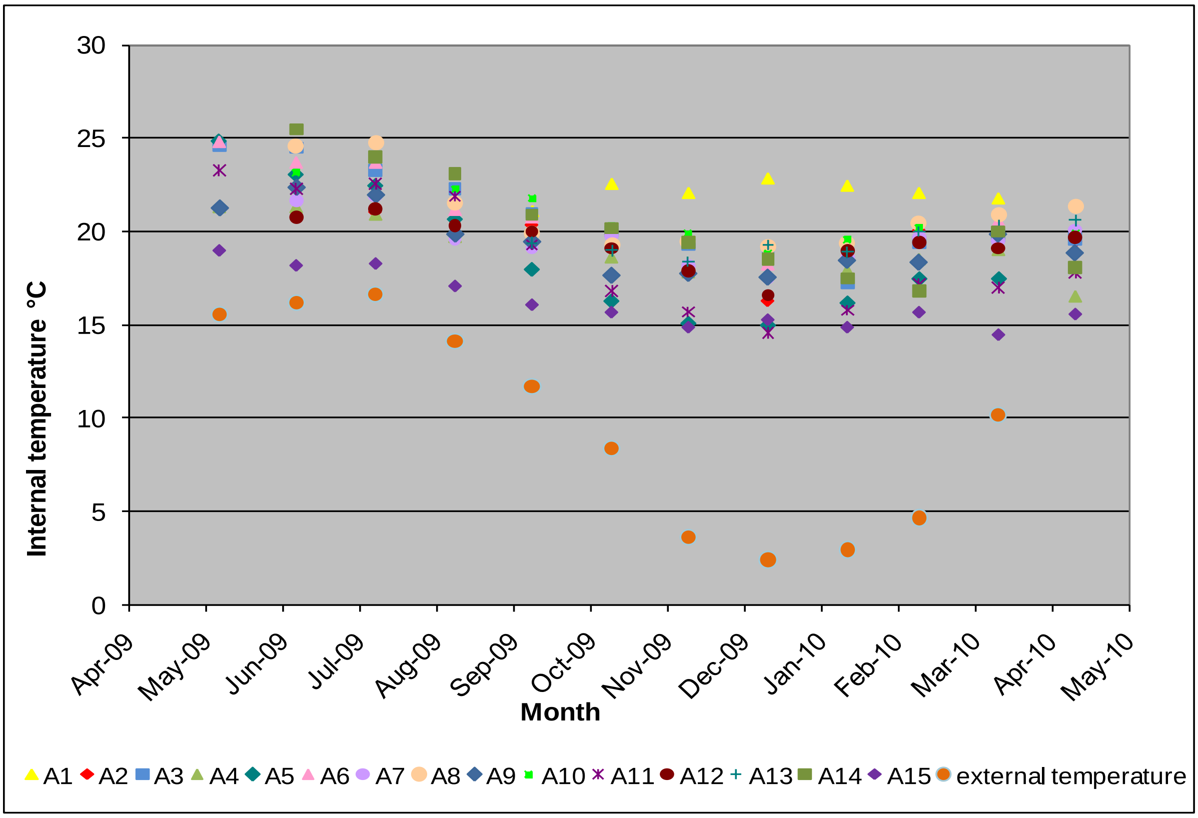


Figure17: Monthly average household temperature

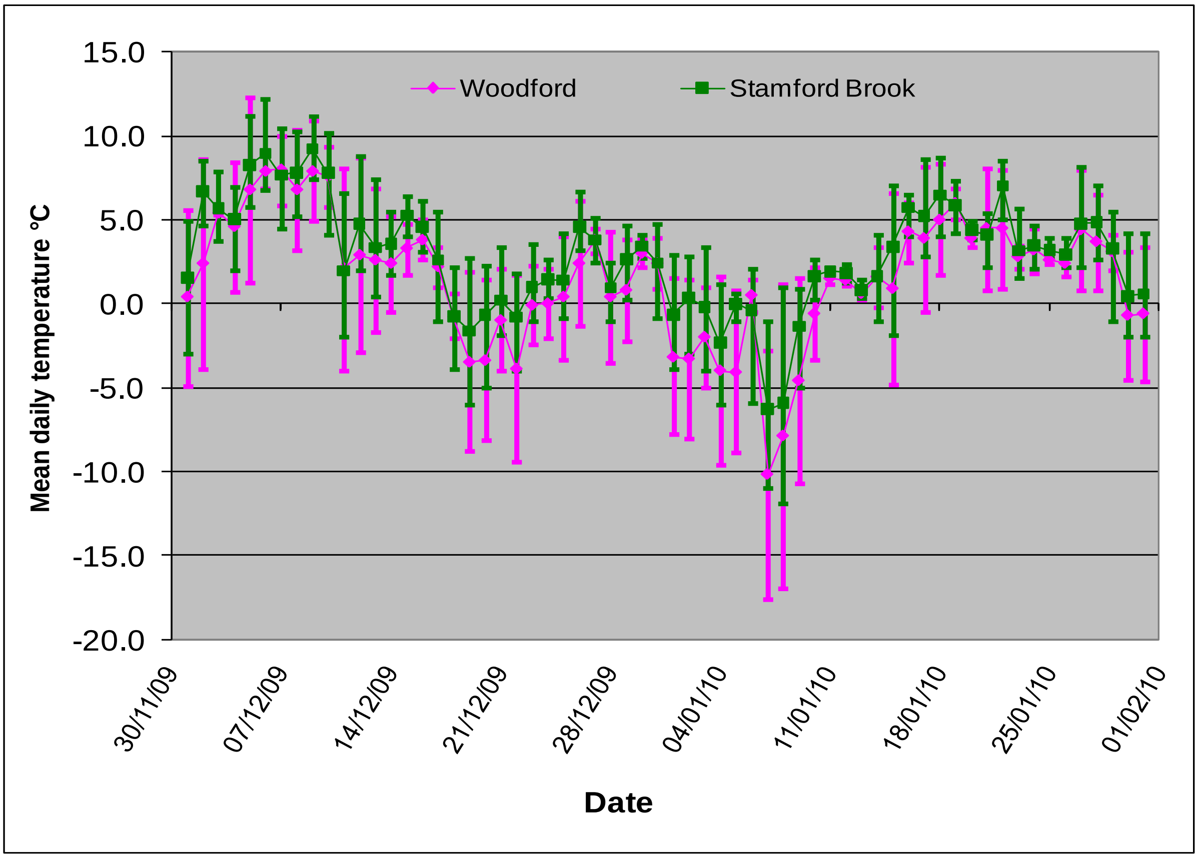


Figure 18: Mean daily temperatures measured at Stamford Brook weather station and the Met Office station at Woodford. Error bars represent the daily range of recorded temperatures.

105. The heating season at Stamford Brook was identified using the weekly gas consumption curve (Figure 4); the change in gradient of the curve was considered to indicate that households had started to use heating within their homes. By using this method the heating season for most houses was identified as occurring from September to May. For the four houses in the original Stamford Brook project, the season was found to run from October to May. External temperatures at Stamford Brook were approximately 14.8°C at the beginning and end of the heating season; this is similar to the typical base temperature adopted by the unadjusted SAP 2005 data and the Carbon Trust heating degree day data of 15.5°C.

106. It was assumed that, outside of the heating period, the householders used other methods to maintain their comfort if the external temperature fell below the base temperature. There are 65 more degree days counted when the whole year is accounted for rather than just the heating season. This would represent a 3% increase in predicted heating demand.

Table 14: Summary of degree day data for March 2009 to March 2010, using a base temperature of 15.5ºC.

Data Source →	**SAP 2005**	**Carbon Trust Data** **7 West Pennines**	**Met Office weather station data**	**On-site weather station**
March 2009	Annual data only	267	//	241
April 2009		184	//	143
May 2009		140	//	110
June 2009		79	//	44
July 2009		39	//	13
August 2009		33	//	7
September 2009		86	//	44
October 2009		160	143.1	118
November 2009		255	234.1	213
December 2009		412	414.6	368
January 2010		477	460.9	421
February 2010		388	366.1	351
March 2010		326	293.5	273
April 2010		218	//	153
Annual value	2130	2342	1913	1997
Heating season		Apr – May 2009; Oct 2010 - Mar 2010	Oct 2009 - Mar 2010	Apr – May 2009; Oct 2009 - Mar 2010

107. It is noted that the degree days values using Carbon Trust and Meteorological Office data are larger than those from the Stamford Brook weather station. Stamford Brook is

located in a heavily developed area, which would be likely to experience some heat island effect, buffering buildings from the extremes of temperature experienced at Woodford airfield. Stamford Brook values were generally lower than the historical data. Figure 18 shows the mean value and range of temperatures measured at the Stamford Brook weather station and the local Meteorological Office station during the cold spell, which occurred across the UK in December/January 2009 - 10. Temperatures at Stamford Brook display a narrower range and are higher than Woodford airfield by up to 8°C, the average difference between 1st December and 31st January was 2.3°. This supports the use of on-site weather stations to derive an accurate picture of heating demand.

PARAMETRIC DOMESTIC ENERGY MODEL

108. Monitoring indicated a normal distribution of energy consumption across the development. By using data collected and the previous understanding of the thermal performance of the dwellings, a model of a “typical” household on the development was created using the Leeds Met/UCL parametric domestic energy model (Lowe *et al.* 2008). The capability of such models to describe thermal performance was assessed by comparing the predicted and actual energy consumption values.

109. Table 15 summarises the “typical” household at Stamford Brook as described by the distribution of house types and floor areas. As the distribution of the floor areas was bimodal, two dwellings have been modelled using the two most frequent floor areas monitored. Thirty-nine of the dwellings were semi-detached or end terrace forms, so this was adopted as the typical form. The smaller house was modelled as a two-storey dwelling and the larger as a three storey as described by the construction drawings. Mean temperature was determined from the internal monitoring data and household occupancy from the questionnaire data.

Table 15: Typical household characteristics at Stamford Brook

Parameter	**Small dwelling**	**Large dwelling**
Floor area /m^2	75	145
Form	Semi-detached	Semi-detached
Number of storeys	2	3
Occupancy	2.2	2.2
Mean internal temperature /°C	17.4	17.4
No. of sheltered sides	2	2
Orientation	South facing	South facing

110. Two models were developed for each dwelling. The first model used as-designed thermal parameters taken from the developer’s specifications. The second model used as-built thermal parameters, which had been developed during the previous research.

111. The predicted energy consumption from each model is shown alongside mean actual consumption for the whole development in

112.

113. Table **16: Modelled energy consumption for “typical” Stamford Brook dwellings. Energy consumption: kWh/a.**

Floor area	**75m2**		**145m2**		**Average**		**Mean Actual Consumption**
	As-designed	**As-built**	**As-designed**	**As-built**	**As-designed**	**As-built**	

Floor area	**75m2**		**145m2**		**Average**		**Mean Actual Consumption**
Electricity /kWh	2,861	2,861	4,490	4,490	3,678	3,678	3,212 (st dev. 1,261)
Gas for space heating /kWh	2,733	2,878	2,971	5,826	2,563	4,352	
Gas for hot water/ kWh	3,088	3,088	2,875	3,088	2,875	3,088	
Total gas /kWh	5,821	5,966	6,354	8,914	5,438	7,440	9,737 (St dev. 2,976)
Total energy /kWh	8,682	8,827	10,844	13,404	9,116	11,118	13,482 (St dev. 3,440)

114. Energy models were developed for the intensively monitored dwellings. Starting with an assessment using as-designed parameters (Level 1), successive assessments were undertaken using increasingly detailed levels of household data to predict values of total energy consumption. Differences between each level of assessment were summarised in paragraph 39 to 43 (Methods).

115. Complete analyses for thirteen dwellings, comprising seven house design types, were completed. Analysis of the apartment was not undertaken because details such as floor and window area were not available; it was not possible to revisit the dwelling to obtain the missing information. Analysis of dwelling A10 was only undertaken to Level 2 because the addition of a conservatory had significantly changed the thermal properties of the building fabric.

116. The parametric domestic energy model calculates hot water demand, consumption by electrical appliances and space heating demand based on construction information. Hot water demand and electrical consumption are determined using algorithms based on floor area, as defined in the BREDEM model and contribute heat to the dwelling. A base (balance) temperature is determined using the construction details and the casual heat gains. Additional heating (required to maintain comfort), is described as space heating and is supplied by the heating system. Space heating does not describe the total heat input to the dwelling and should be considered alongside the other energy consumption when the thermal performance of the fabric is considered.

117. . The predicted value was 32%[*] smaller than the actual consumption using as-designed parameters. Using as-built parameters, the predicted consumption was 17.5% smaller than the actual consumption, which falls within 1 standard deviation of the mean.

Table 16: Modelled energy consumption for "typical" Stamford Brook dwellings. Energy consumption: kWh/a.

Floor area	**75m^2**		**145m^2**		**Average**		**Mean Actual Consumption**
	As-designed	**As-built**	**As-designed**	**As-built**	**As-designed**	**As-built**	
Electricity /kWh [†]	2,861	2,861	4,490	4,490	3,678	3,678	3,212 (st dev. 1,261)
Gas for space heating /kWh	2,733	2,878	2,971	5,826	2,563	4,352	
Gas for hot water/ kWh	3,088	3,088	2,875	3,088	2,875	3,088	
Total gas /kWh	5,821	5,966	6,354	8,914	5,438	7,440	9,737 (St dev. 2,976)
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[*] The percentage difference is with reference to the actual consumption. Difference = {(Actual –Predicted)/Actual }*100%

[†] Electricity consumption based on the assumed occupancy and the lighting algorithms in the model.

121. Figure 19, Figure 20 and Figure 21 present the results of the modelling. The results have been arranged to present similar house types together, with actual and predicted consumption for each dwelling presented next to each other. Table 17 presents the results as a percentage of total consumption.

122. Level 1 models used as-designed values for fabric and system performance. Values for occupancy, electricity and hot water demand are based on algorithms linked to floor area and weather data are from the SAP data base. Predictions of consumption ranged from 57% to 123% of actual consumption. Actual consumption was greater than predicted for 71% of the dwellings. No correlation between dwelling form or size was identified in the magnitude of difference between predicted and actual consumption.

123. The actual household conditions could affect the prediction in either direction; however, most households had fewer occupants than predicted by the SAP model. Half of the households were occupied during the day and the evening. In addition, the number of degree days used within the SAP model was greater than the number based on the on-site weather station.

Figure 19: Level 1 Predicted values with actual consumption.

124. Level 2 predicted energy consumption; using as-built parameters and degree day data from the on-site weather station, is presented in Figure 20. Predicted consumption ranged from 60% to 147% of actual consumption, with 6 of the predicted consumption values within 10% of actual consumption. The increase in predicted energy consumption is due to using the lower values for as-built thermal performance, as opposed to as-designed performance.

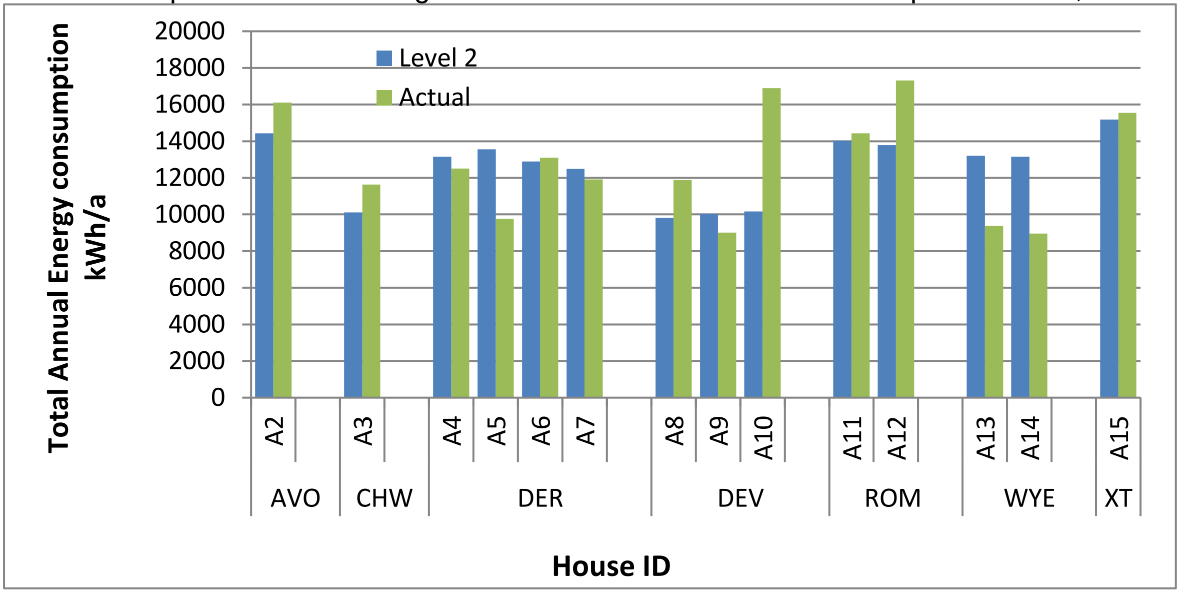

Figure 20: Level 2 Predicted values with actual consumption

125. Level 3 models included all household data collected during the research, internal temperature, and air tightness (where available), degree day data, occupancy data and actual electricity consumption. Predictions of consumption ranged from 75% to 144% of actual consumption. 5 models predicted consumption to within 10% of actual consumption. Figure 21 shows the Level 3 predicted consumption alongside actual total energy consumption.

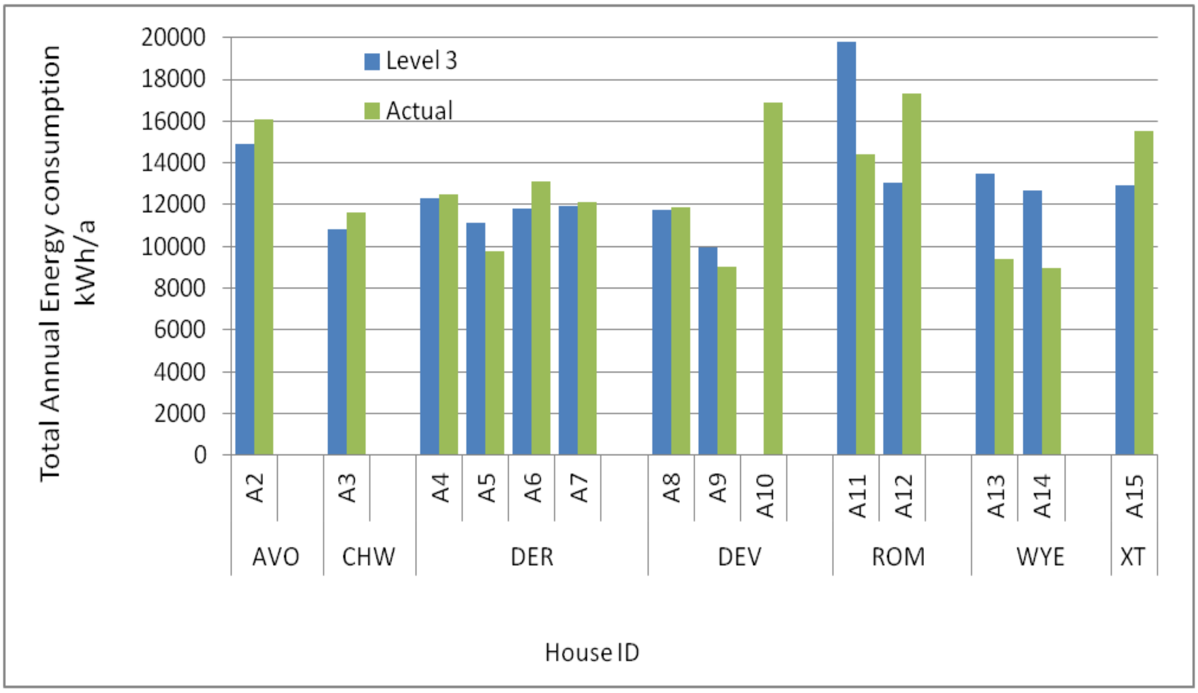

Figure 21: Level 3 Predicted values with actual consumption

126. Table 17 details the differences between the actual and predicted consumption for each dwelling. The difference between the levels of data was not statistically significant and not all dwellings' models showed improved prediction as the detail increased.

Table 17: Summary of predicted consumption as a percentage of actual consumption

House	Design	Level 1	Level 2	Level 3
A2	AVO	85%	90%	93%
A3	CHW	67%	87%	93%
A4	DER	89%	105%	98%
A5	DER	115%	139%	114%
A6	DER	85%	98%	90%
A7	DER	94%	105%	98%
A8	DEV	81%	83%	99%
A9	DEV	105%	112%	111%
A10	DEV	57%	60%	--
A11	ROM	86%	97%	137%
A12	ROM	72%	80%	75%
A13	WYE	118%	141%	144%
A14	WYE	123%	147%	142%
A15	XT2	82%	98%	83%

Average percentage difference	19%	18%	17%
Standard deviation	10%	16%	15%
No. within 10% of actual consumption	2	6	6

Table 18: Summary of Percentage difference between predicted and actual consumption

House	Design	Level 1	Level 2	Level 3
A2	**AVO**	**15%**	**10%**	**7%**
A3	**CHW**	**33%**	**13%**	**7%**
A4	**DER**	**11%**	**5%**	**2%**
A5	**DER**	**15%**	**39%**	**14%**
A6	**DER**	**15%**	**2%**	**10%**
A7	**DER**	**6%**	**5%**	**2%**
A8	**DEV**	**19%**	**17%**	**1%**
A9	**DEV**	**5%**	**12%**	**11%**
A10	**DEV**	**43%**	**40%**	**-**
A11	**ROM**	**14%**	**3%**	**37%**
A12	**ROM**	**28%**	**20%**	**25%**
A13	**WYE**	**18%**	**41%**	**44%**
A14	**WYE**	**23%**	**47%**	**42%**
A15	**XT2**	**19%**	**2%**	**17%**
Average percentage difference		**19%**	**18%**	**17%**
Range of accuracy		**5 - 43%**	**2 - 47%**	**2 - 44%**

127. The results in tables 17 and 18 show wide variations in the accuracy of energy use prediction at levels 1, 2 and 3 of the model. Table 17 shows the increased level of detail included in levels 2 and 3 results in a larger number of predictions within 10% of actual energy use compared to level 1 models, showing some increase in accuracy. However, both levels 2 and 3 have six predictions within 10% of actual energy use, showing no significant increase in accuracy between level 2 and 3. Table 18 shows that the average percentage accuracy of the model does increase from level 1 to 3, though the increase is small. The range of percentage accuracy of levels 2 and 3 are both larger than level 1, possibly due to the difficulty of modelling occupant behaviour.

Back modelling

128. Using the Leeds Met/UCL parametric domestic energy model (Lowe et al., 2008) back modelling was undertaken to derive whole heat loss coefficients and thus heat loss parameters, from the actual energy consumption for the intensively monitored dwellings. The parametric energy model was constructed, using mean internal temperature, occupancy and the known energy consumption values, except space heating. The heat loss coefficient and the number of degree days were then adjusted within the model to give values for space heating. Iterative adjustment of the whole-

house heat loss was undertaken to deliver a predicted space heating demand within 10% of actual consumption. Once a heat loss coefficient had been derived, a heat loss parameter could also be determined.

Table 19: Heat loss coefficient derived using only energy consumption data

House	Design	Heat loss coefficient (W/K)	Heat loss parameter (W/m^{2}K)			Notes
			As designed	As built	Back modelling	
A2	AVO	162.1	1.2	1.2	1.2	
A3	CHW	72.0	1.0	1.6	1.0	
A4	DER	83.52	0.9	1.2	1.1	
A5	DER	114.7	0.9	1.3	0.9	Hot water supplied by immersion & defective boiler
A6	DER	114.7	0.9	1.4	0.9	
A7	DER	114.7	0.9	1.2	0.9	
A8	DEV	114.7	1.3	1.5	0.9	
A9	DEV	105.2	1.3	1.6	1.3	
A10	DEV	102.8	1.3	1.6	1.2	Significant change to fabric
A11	ROM	135.9	1.0	1.5	1.0	Hot water supplied by immersion
A12	ROM	135.9	1.0	1.2	1.0	
A13	WYE	122.2	1.2	1.5	1.2	
A14	WYE	122.2	1.2	1.5	1.2	
A15	XT2	103.7	1.1	1.3	1.0	
Average		116.8	1.1	1.4	1.1	
Standard Deviation		23.1	0.2	0.2	0.1	

Table 20: Heat loss coefficient derived using internal monitoring and energy consumption data.

House	Design	Heat loss coefficient (W/K)	Heat loss parameter (W/m^{2}K)			
			As designed	As built	Back modelling	
A2	AVO	210.0	1.2	1.2	1.6	
A3	CHW	104.0	1.0	1.6	1.4	
A4	DER	167.0	0.9	1.2	1.4	
A5	DER	161.0	0.9	1.3	1.3	Hot water supplied by immersion & defective boiler
A6	DER	180.0	0.9	1.4	1.5	
A7	DER	139.0	0.9	1.2	1.3	
A8	DEV	137.0	1.3	1.5	1.6	

A9	DEV	101.0	1.3	1.6	1.2	
A10	DEV					Significant change to fabric.
A11	ROM	215.4	1.0	1.5	1.3	Hot water supplied by immersion
A12	ROM	202.0	1.0	1.2	1.5	
A13	WYE	124.0	1.2	1.5	1.2	
A14	WYE	118.0	1.2	1.5	1.1	
A15	XT2	167.0	1.1	1.3	1.3	
Average		151.8	1.1	1.4	1.4	
Standard Deviation		34.8	0.2	0.2	0.2	

129. Tables 18 and 19 show the results of the back modelling, using differing levels of data. The heat loss parameters given by the model when using only energy use data (table 18) are significantly lower than the actual values derived from co-heating tests. The heat loss parameters given when internal monitoring and energy use data were used are much closer to the actual values, though the standard deviation of 0.2 and the results show there is still a degree of error.

DISCUSSION

130. There has not been a tradition of monitoring the energy consumption of dwellings (Leaman *et al.* 2010) and as such, there is a poor understanding of whether they function as-designed. Recent studies identified that there are performance gaps, where the designed fabric and systems performance of dwellings is not achieved (Bell *et al.* 2010; Wingfield *et al.* 2008). Given the need to progress towards the reliable construction of energy efficient dwellings, it is vital that the construction industry is able to assess whether the buildings they construct perform as expected and how householder behaviour affects the energy performance of a dwelling.

131. The research here enables the exploration of energy consumption data from a large number of dwellings for which there are fabric performance data. This report focuses on whether the fabric performance can be derived from the basic meter reading data and what additional information is required to determine fabric performance accurately. Data were analysed in different sets and subsets, from individual dwelling profiles to the annual profile across the development, and patterns within the data highlighted conditions within the dwelling, which affect energy consumption.

Comparison of consumption with other developments

132. The participation of a larger number of dwellings than in the original Stamford Brook research project enabled greater confidence in the statistical description of the typical energy consumption of the monitored dwellings. The monitoring carried out during this project indicated a greater total range of energy consumption across the development than was shown in the previous research, the entire range of which fell within the interquartile range described by the data set gathered during this project.

Table 21: Summary of Stamford Brook average energy consumption

	Electricity kWh/a	**Gas kWh/a**	**Annual Energy Use kWh/a**
Stamford Brook mean	3,371	10,357	14,140
Standard deviation	1,606	3,798	4,428

Previous Stamford Brook Research [1]	2,506 -3,086	6,444 -12,835	8,590 -15,921

133. Gallions Ecopark (DVA 2004) and Elm Tree Mews (Bell *et al.* 2010) are developments of similar age to Stamford Brook and were also built with a focus on achieving high energy efficiency. Gallions Ecopark housing development in Thamesmead was constructed using a prefabricated timber panel system heated using condensing gas boilers and were supplied with solar hot water. 13 dwellings had their gas use monitored. Despite the availability of solar hot water the dwellings at Gallions Ecopark have higher gas consumption than the mean at Stamford Brook, this is summarised in Table 21. Elm Tree Mews is a Joseph Rowntree Housing Trust (JRHT) development in York designed to meet the Government's carbon targets for 2013 and incorporates energy efficient heating technology. Five dwellings were monitored and showed a range of consumption lower than those at Stamford Brook although this may have been produced by the smaller sample size. Mean monthly internal temperatures at Stamford Brook were similar to 4 of the 5 Elm Tree Mews houses with temperatures between 15 and 20°C. The range of consumption at Stamford Brook could be reflected at Elm Tree Mews and Gallions Ecopark if larger data sets were available. Small data sets may give a distorted impression of overall performance of the developments.

Table 22: Gallions Ecopark Monitored Energy Data (DHV 2004) data presented as the range of data across the dwellings.

Dwelling Type	**Mean Measured Total Gas Use (Including gas for cooking) (kWh/a)**
Stamford Brook	Average: 10,357 standard dev.: 3,798
Gallions Ecopark	9,386-12,833

Table 23: Stamford Brook and Elm Tree Mews field trial energy consumption data. Consumption presented as total range of consumption across the monitored dwellings.

	Space heat	**Hot water**	**Lights and appliances**	**Total energy consumption**	**Normalised total energy consumption**
	kWh/a	kWh/a	kWh/a	kWh/a	kWh/m^2/a
Stamford Brook	270-12,418	1,172-15,422	667- 9,574	6,550-31,500	74.0 - 290.5
Elm Tree Mews	787 – 4,556	626 – 1,265	526 - 4,275	2,014 - 9,417	37.3 - 83.1

134. OFGEM values, used to provide an indication of typical UK energy consumption, are presented in Table 24. Values of low, high and medium consumption are calculated

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[1] The data has not been corrected to account for different weather conditions or other factors

using the lower and upper quartile and the median of national values. The distribution of consumption shown in

136. **Table 9** indicates that the average households at Stamford Brook are in the first quartile; however, the highest consumers have consumption in the upper quartile. On average households at Stamford Brook are smaller, with an average of 2.2 persons, compared to the UK average of 2.4 (ONS 2009). The largest consumer at Stamford Brook had an occupancy of 7. Similarly, DECC data indicates that Stamford Brook households consume less than average.

Table 24: Current standard annual gas and electricity consumption (OFGEM, 2011; DECC, 2008)

Average Annual Consumption	Electricity (Standard) (kWh)	Gas (kWh)
OFGEM Low	2,100	11,000
OFGEM Medium	3,300	16,500
OFGEM High	5,100	23,000
DECC – Quarterly Energy Prices 7	3,300	18,000
DECC: Trafford	4,308	19,385
DECC: UK	4,478	16,906

137. In the summer, the range of consumption observed was narrower than in the winter. This is caused by the larger number of factors affecting winter consumption; including fabric performance, mean internal temperature and heating patterns. While the range of total annual consumption was 24,984kWh, the interquartile range of consumption was narrow, 50% of householders had annual consumption within a 5,000 kWh/a range. The highest 25% of total energy consumers were responsible for over a third of the total energy consumption. This suggests that there is a potential for a number of households to reduce their consumption. However, if only the magnitude of the household's consumption and not the contextual information is considered, there is failure to acknowledge that energy consumption is the result of people's activities, rather than people's decision to consume energy. This is exemplified by the highest total energy consumer also having the largest household in terms of the number of occupants, with seven permanent members of the household, plus frequent visitors. This is much larger than the average 2.2 household members. When normalised for occupancy, their electricity demand is 1,367 kWh/a per household member, which is typical for the development. Furthermore, space heating was lower than similarly sized dwellings and the householder indicated that they rarely used space heating.

Normalised energy consumption

138. The participating households consist of a range of house types, have different numbers of people in the household and have different occupancy patterns. These among other factors affect their energy demands. In order to enable the direct comparison between dwellings, energy consumption was attributed to different types of demand; space heating, hot water, cooking and electricity; these demands were then normalised with respect to floor area and occupancy.

139. Annual hot water demand was calculated by adjusting the summer gas consumption, as described in the methods, this is considered a good estimate. It is anticipated that energy consumption for hot water demand would be larger in the winter than the summer because the lower mean internal temperatures lead to greater pipework heat losses within the house, for the purposes used here, these values are sufficiently accurate. Using summer consumption to determine the yearly consumption, it was assumed that the household has remained the same over the monitoring period. Changes in household circumstances, such as, the number of occupants within the

household, employment status and occupancy patterns would have affected patterns of demand and thus energy consumption associated with hot water demand and cooking. Two householders informed the research team that their dwelling would not be occupied during the winter and the analysis was adjusted accordingly. However, these data were not collected from the whole sample group.

140. There is significant variation in total hot water and cooking energy consumption across all dwellings; and average consumption per household occupant, despite 83% of households comprising 1-2 adults with no children or one child. The lack of correlation identified between energy demand for hot water and occupancy indicates a broad range of boiler system efficiencies, differences in hot water demanded and heating strategies. The hot water systems at Stamford Brook are comprised of a hot water storage cylinder connected to a boiler and a timer system that allows the householder to choose the heating profile. Hot water consumption was not measured directly so it is unknown whether the hot water consumption and the energy used to meet the demand have a strong correlation. During the previous research at Stamford Brook, one household reduced their period of heating for hot water from 4.5 hours each day to 0.5 hours over one heating period and did not need to alter their hot water usage. This indicates that some households may be heating their hot water unnecessarily. In order to accurately model energy consumption, more detailed monitoring using heat meters and secondary electricity and gas meters would be required.

141. The space heating demand expresses the additional heating required to raise the dwelling temperature above base temperature, to the desired internal temperature. Base temperature is affected by casual gains from environmental conditions; such as solar gains; and householder activity: metabolic gains, incidental gains from electricity use and hot water use. No correlation was identified between space heating demand and floor area, reflecting the variations in casual gains. A better correlation between total consumption and floor area was identified; however, the correlation remained weak; reflecting further differences in behaviours such as window opening, occupancy patterns and internal temperature, which influence heat demand and loss.

142. No significant correlation was identified between electricity consumption and occupancy. Comparison was limited, comparing the total number of occupants, and did not account for the difference between the number of adults versus children or take their patterns of occupancy or the number, types and usage patterns of appliances into account.

143. Dwellings were ranked according to the magnitude of hot water demand, and then by space heating demand, then by total gas consumption. No correlation was found when the rankings were compared. This is expected due to variation in sizes of dwellings and occupancy and other factors, but is noted here in order to reinforce the need to understand the household context to compare even similar dwellings. If thermal performance is to be determined from energy consumption then data must be collected at a resolution sufficient to disaggregate hot water and space heating; monthly data would be required at a minimum.

144. The identification of the party wall as a significant heat loss element during the previous research (Wingfield et al. 2008) suggests that a difference in thermal performance of the dwellings may be related to the number of party walls present. The average energy consumption of detached dwelling (no party wall bypass), semidetached and end terrace dwellings (1 bypass), mid-terrace (2 bypass), and apartment (unknown) were compared. No significant difference between dwelling forms was identified.

145. Total energy consumption of dwellings was also considered with respect to the number of storeys. The number of storeys was an indicator of dwelling size; also, the 2.5 storey dwellings had more complicated design details, which had been identified as problem areas during construction, such as knee walls. No difference was found.

Similarly, no grouping was identified within the pressurisation test results.

146. The lack of any significant correlation between total energy consumption, electricity consumption, hot water and cooking and space heating with floor area and occupancy is related to the complexity of energy consumption. Different households have different behaviours, which coupled with varying system performance produces the range of consumption observed. As such, there is scope for reducing energy consumption by making different choices. The resolution of the monitoring undertaken here is not sufficient to determine decision-making processes. More frequent readings and additional metering of actual energy consumption for hot water, cooking and individual appliances coupled with more in depth information about the households' behaviours for achieving thermal comfort would be required to build up a more detailed understanding of dwelling thermal performance and design feedback to householders.

Consumption profiles

147. Within the development, the energy consumption varied from week to week. The gas and electricity profiles had a similar shape showing low levels of consumption with little variability occurring through the summer. The external temperature at which dwellings commenced using their heating was approximately 15.3°C. Consumption increased as external temperatures fell below 15.3°C and daylight hours fell. Peak demand coincided with Christmas and the winter solstice. The heating season, described by these conditions occurred between 1st October and 31st May.

148. During the heating season, gas and electricity consumption inversely followed external temperature. Increased winter electricity consumption was attributed to increased demand for power from the boiler, increased occupancy, lighting demand and increased use of the electric oven for hot meals. Increases in gas and electricity occurred at the same time suggesting that the same controlling factors affected their demand and were attributed to lower external temperatures and less daylight. Peak consumption occurred during the Christmas period and the winter solstice. The lowest external temperatures and levels of daylight occurred over this period. In addition, dwellings may have been occupied for longer periods during the Christmas holidays as households, which are usually at work during the daytime, were at home and heating the dwelling. There may also have been additional demand for services, such as, hot water demand, cooking and electrical demand for lighting and appliances over this period.

149. Individual household profiles were described within the results section. The wide range of energy usage in the household profiles highlights the need for greater understanding of householder behaviour in order to interpret the gathered data fully. Individual behaviours have little effect on the consumption profile of the development as a whole, but it can be reduced by the efficient management of each household's consumption in order to achieve comfort, resulting in reductions in energy consumption and subsequent carbon dioxide emissions. For a householder to optimise their energy consumption they need to understand the impact of their decisions. The use of electrical heating and the continuous use of the immersion heater indicate that some householders were not fully informed on the systems in their home or the impact of their choices.

150. Identifying failures in system performance was possible through a number of measures. One householder approached the team and highlighted their concern. From this, it was relatively easy to identify that their immersion heater was on continuously and subsequently, that their boiler was broken. The fact that the contractors had not identified this when they had been contacted is of concern and displays the failure of the commissioning and snagging procedures, which are in place.

151. For the household only using the immersion to meet hot water demand, gas consumption of the dwelling sat within the normal range of consumption described by

the statistics gathered. The presence or absence of outliers thus does not necessarily indicate problems with fabric or systems performance but, by their nature, should be investigated.

152. The risk that this and similar problems are not identified could be exacerbated by the use of direct debit bill payments, estimated bills and paperless bills which make it unnecessary for a householder to review their consumption prior to making payment. The checking of payments, and noting unusually high bills would be one way of identifying excessive consumption, however, it is noted that when one of the householders did contact the energy supplier, following what they considered were high bills, they were informed that their consumption was within the typical range.

153. Improvements enabling the householder to identify problems will not remove the need for developers to demonstrate that the houses are performing as designed. Testing of all systems to ensure that they work correctly is part of the commissioning process, that problems persist highlights deficiencies in this process. The period of contact between the householder and the developers following handover; the snagging process, could be extended to not only deal with problems but also to review how the householder uses their systems and to offer operational advice.

Use of the parametric domestic energy model

154. In order to assess the in-use performance of dwellings against the design expectations, reliable models are required. The “typical household” model predicted total consumption to within one standard deviation of the mean actual consumption; using the as-built parameters. The use of larger sets of energy consumption data increases the confidence in the mean consumption value and the use of two models to describe the housing model enabled a more representative picture of the housing to be developed.

155. The as-built fabric performance values were derived from co-heating test data, thermal imaging, observation of the construction process and modelling. They have been assumed to provide more realistic fabric performance values for all the model dwellings than the as-designed parameters. It is recognised that while these values are an improvement with respect to the design values, they are approximate if applied to dwellings other than the tested dwelling; there will be an error associated with the values when used within predictive models. There will be variations in the magnitude of heat loss and the dominant heat loss mechanisms between individual dwellings, due to inconsistencies within the construction of the individual dwellings that are not accounted for by the use of approximate values.

156. The data included within each level were determined by the data collection method. Levels 1 and 2 did not require data collection during the occupation of the dwelling, other than energy consumption data. Level 3 models were only used for the modelling of individual dwellings; they incorporated data from internal temperature monitoring which required access to the dwelling and householder consent. In the long term, it could be envisioned that temperature sensors could be incorporated into individual rooms as part of the household energy management systems.

157. No significant improvement in the models predictive accuracy was identified between Level 1 and 2. The addition of monitoring data led to less accurate prediction for 6 of 13 cases between Level 2 and 3, which reinforces the complexity of household behaviour and the difficulty of modelling individual households.

158. The use of individual households reduces the range of actual consumption to a single known value, but the counterpoint is that individual behaviour strongly affects the consumption pattern. The individual behaviour can be complex and difficult to predict; as such, any models incorporating assumptions of behaviour can only be expected to be accurate within the range defined by that complexity. At Level 3, with all the available

monitoring data, predicted values still varied from the actual consumption by up to 44%.

159. It has not been possible to resolve the difference between predicted and actual energy consumption for each modelled dwelling. For the dwellings at Stamford Brook, the models, coupled with the energy consumption data, indicated that performance did not meet the design performance because of the large discrepancy between as designed predictions and actual consumption. However, as thermal performance of dwellings improve, the space heating demand will become a smaller part of the total consumption; incidental heat gains will represent a much larger part of the total heat requirement of the dwelling and the additional energy required to maintain higher internal temperatures will lessen. This will make it more difficult to separate the variation produced by differences between households behaviour from differences produced by underperformance of the dwelling systems and fabric.

160. Back modelling of the energy consumption data was undertaken to derive heat loss parameters for the monitored dwellings. The average heat loss parameter was 1.1 W/m^{2}K (st dev 0.1) using only energy data and 1.4 W/m^{2}K (st dev 0.2) incorporating monitoring data into the model. The heat loss parameters derived from the co-heating tests undertaken previously were 1.2 - 1.4 W/m^{2}K. This suggests that back modelling enables a general picture of performance to be achieved if household information is available; more detailed energy monitoring data is likely to allow more accurate modelling of heat loss parameters. This method does not inform on how heat transfer occurs through the dwelling fabric, though it could indicate the presence of a problem.

Limitations

161. It was not the purpose of the research to consider how to affect household consumption. Householders were provided with their meter readings each week but no further information was provided. It is unknown whether this information affected behaviour, as no control group (where meter readings were not fed back) existed for comparison. No analysis was undertaken, and householders were not asked about their response to the information provided.

162. Unfortunately, the assessment of apartment dwellings at Stamford Brook has been limited. This was the result of limited access to the apartment buildings, which prevented the full energy consumption data set from being collected. Apartments could not be described collectively because they were different sizes and had different numbers of party elements and external walls.

163. The accuracy of the data inputs to the parametric energy model are limited to the resolution of the monitoring undertaken. More intensive monitoring separating energy demands: cooking, hot water and space heating would allow the separation of the energy uses. Further monitoring could improve inputs for boiler efficiency, ventilation rates, and household behaviours. However, additional monitoring requires additional equipment, data processing and consideration and if not installed during the building process requires the householder to allow access to the dwelling for a number of trades.

164. The difficulty of predicting the impact of occupant behaviour on household energy use was compounded by the lack of pre-occupation energy performance data. Though these data existed for a small set of dwellings, they were not available for the majority. Where they were not present, approximate data were used, leading to uncertainty differentiating between issues with building performance and occupant behaviour.

165. Though the sample size used in this project is large when compared to similar projects mentioned in this report, there is still scope to use larger sample sizes. The Stamford Brook development consisted of 400 dwellings at the time of the monitoring, had a greater number of households taken part in the project a greater depth could have been leant to the data gathered.

CONCLUSIONS AND RECOMMENDATIONS

166. . The research enabled the description of energy consumption across a large development, from the individual household to the development as a whole. The aim of the report was to identify what additional data collection was needed to explain patterns of energy consumption in buildings. The following three data collection methods enhanced the descriptive capacities of energy data, each being progressively more invasive yet more revealing:

- Desktop surveys to establish ‘housing type’ sub categories to refine the data sets (number of bedrooms; whether they are terrace, mid terrace, semidetached of flats; construction type).
- Remote questionnaires to gather data on occupancy and heating habits.
- Post occupancy site visits to assess system commissioning and handover.

167. Employing these methods allowed more accurate identification of unusual energy consumption. In addition they often identified the causes of abnormal behaviour so that solutions could be sought. Without this additional contextualisation, seemingly normal energy consumption in a dwelling, which was actually inefficient (and vice versa) may not be picked up through analysis of the energy data alone.

168. The implications of this finding are potentially large as smart metering becomes more widespread. Approaches to educate and inform building occupants about energy consumption using only energy data derived from smart meters could lead to trends being missed or even misinterpreted without additional contextual knowledge of the building’s fabric, it’s systems or occupants. Future research may be useful to understand in more detail the scale to which each additional factor influences the predictive power of energy data.

169. This has implications for predicting the payback rates of particular energy efficiency measures, for example in the Government’s Green Deal scheme. If a degree of historic energy data were gathered in addition to a few contextualising data points then additional understanding of the home’s current energy use and efficiency could be understood which would make the payback predictions more realistic and specific. Without this, homes are assumed to react homogenously which this report has shown is not the case and this may result in some predictions made about the performance of interventions inaccurate.

170. Average household energy consumption was within the lower quartile of UK consumption and compared favourably to dwellings of similar age and design aims. While the interquartile range of consumption was between 13,000-16,000kWh/a, the household with the highest consumption consumed 31,531kWh/a. This was more than twice the consumption of most other households in the development and is in the upper quartile of UK consumption. This high consumption is a result of the household’s high occupancy, their per person consumption was comparable with the rest of the development.

171. Most of the development (86%) had fewer than three occupants. The range of consumption shown across households indicated the degree to which households’ behaviour affected their consumption. More intensive monitoring of the dwellings would be required to come to any solid conclusions, but the research indicates that there is significant variation in hot water demand, cooking and electricity consumption across the dwellings. Internal temperature was found to vary between dwellings, and vary in each dwelling throughout the heating season as external temperature varied, suggesting that the households could achieve comfort with reduced internal temperatures during swing seasons.

172. Despite this range of consumptions across the dwellings, the unintended use of the immersion heater could be identified in the individual dwelling profiles; when compared to the average for the house type, as low gas and high electricity consumption. Metered data could be used to highlight unusual usage patterns, looking at long term consumption trends for an individual household and by comparison against other similar households. For the individual householder, using short term data, e.g. a monthly rolling average, a household would be able to identify changes in its consumption pattern over the midterm. Variation across the year indicates that seasonal corrections are required, using local data and comparing data from successive years would enable the clearest comparison.

173. If householders are to respond to information they are given, they need to understand the systems in their home. There is evidence to suggest that some householders do not understand how the systems in the dwelling work and interact, are not able to manage their systems and have misconceptions about the most economical and lowest carbon ways to achieve comfort. As such, there is scope for improvements to be made to the handover process.

174. Modelling was undertaken to explore whether energy consumption data could be used to indicate dwelling thermal performance. The number and complex interaction between factors, which affect energy consumption, cannot be completely captured in models. Models using all available details: household data and proxy values of thermal performance, gave predicted values within 44% of the actual consumption. While the use of household information improved the model, no individual parameter; relating to the dwelling or the household, significantly improved the validity of the model in every case. Instead, a complex interaction of household behaviour and fabric performance was found to affect consumption

175. Back modelling, using monitoring data to derive a building heat loss parameters was undertaken on the intensively monitored dwellings. The results of the back modelling indicated that the using more detailed data results in more accurate results, the accuracy of back modelling could potentially be improved with the use of more comprehensive monitoring. The use of back modelling presents a potential alternative to the laborious and expensive testing methods currently used in the construction industry.

176. The measured internal temperature data have shown that households use their dwellings in many different ways across the development; it would be difficult for any model using standardised assumptions about occupancy and in-use factors to model energy use accurately. As dwellings become more efficient and the required space heating demand reduces, the variation produced by behaviour becomes a larger proportion of the total value. As such, it is unsuitable to use the SAP model, without adjustment, to assess the performance of as-built construction

177. Models of the typical household suggested that the adjusted values for thermal performance, derived from coheating tests were more representative of the actual performance than the design values. However, modelling also showed that the performance values taken from the coheating test might not be applicable to all dwellings on the site. Predicted consumption for individual dwellings tended to improve when the adjusted values were used, but not in every case.

REFERENCES

ANDERSON, B.R. CHAPMAN, P.F. CUTLAND, N.G. DICKSON, C.M. HENDERSON, J.H. ILES, P.J. KOSMINA, L. AND SHORROCK, L.D. (2002) *BREDEM-12 Model Description: 2001 update*, Building Research Establishment, Garston

ATTMA (2007) *Technical Standard 1: Measuring Air Permeability of Building Envelopes* [Internet]. Airtightness Testing and Measurement Association Issue 2, 13th July 2007. Available from: http://www.attma.org [Accessed 2nd July 2010].

BAUWENS, G. (2015) In-situ testing of a building's overall heat loss coeffieient. Embedding quasi-stationary and dynamic tests in a building physical and statistical framework. Published PhD KU Leuven, Arenberg Doctoral School, Faculty of Engineering.

BOARDMAN, B. (2007), *Hometruths*, University of Oxford, Environmental Change Institute. Available from http://www.eci.ox.ac.uk/research/energy/hometruths.php [Accessed 21st October 2010]

BRE (2004) *Client Report: Assessment of energy impact of building regulations compliance.* Client report number 219683. Available from http://www.eeph.org.uk/Publications [Accessed 15th September 2010]

BRE (2005) *The Government's Standard Assessment Procedure for Energy Rating of Dwellings – 2005 Edition – v9.8*, BRE, Garston, Watford

BRE (2010) *The Government's Standard Assessment Procedure for Energy Rating of Dwellings*, 2009 Edition, version 9.90, 23rd March 2010, Building Research Establishment, Garston. Available from http://www.bre.co.uk/filelibrary/SAP/2009/SAP-2009_9-90.pdf [Accessed 3rd April 2010]

BUTCHER B. & HERRING C; (2010) *A Very British Passivhaus*; Vol. 20, Issue1; Green Building Magazine

CARBON TRUST (2007); *Degree days for energy management- a practical introduction*. Report ref: *CTG004*.

CARBON TRUST (2010) Available from http://www.eci.ox.ac.uk/~rlayber/weekly_updated_data/weekly/Woodford_weekly_hdd.csv [Accessed 10th June 2010]

CARBON TRUST (2011) *Historical Degree Day Data, collated by Degree Days Direct;* Available from *http://www.carbontrust.co.uk/cut-carbon-reduce-costs/calculate/energy-metering-monitoring/pages/degree-days.aspx* [Accessed between May 2009 and June 2010]

CLG (2007) *Building a Greener Future – Policy Statement.* Department for Communities and Local Government. Available from http://www.communities.gov.uk/documents/planningandbuilding/pdf/building-greener.pdf [Accessed 1st July 2010]

CONSUMER FOCUS (2009) NORWEB, 19 August 2009, *Price comparison sheet*. Available from http://consumerfocusapps.vph.co.uk/Frontend/assets/pricecomparison/PriceComparison_Norweb_19August2009.pdf [Accessed 10th January 2011]

DECC (2008) *Climate Change Act 2008.* Department for Energy and Climate Change, London, HMSO

DRUCKMAN, A AND JACKSON,T (2008) *Household energy consumption in the UK: A highly geographically and socio-economically disaggregated model.* Energy Policy vol.36. pg 3177– 3192

DTI (2006) *Energy – Its Impact on the Environment and Society, Annex 3B - Regional and Local Use of Energy in the Domestic Sector*, Department of Trade and Industry, Available from http://www.dti.gov.uk/files/file20328.pdf [Accessed on 12th September 2009]

EBA ANNEX 71 (2016) Building Energy Performance Assessment Based on Optimized In-situ Measurements. Energy Buildings Communities Programme. International Energy Agency. http://www.kuleuven.be/bwf/projects/annex71/

GORSE, C. A, GLEW, D, MILES-SHENTON, D, FARMER, D and FLETCHER M. (2013) Building Performance: Fabric, impact and implications, Sustainable Building 2013 Hong Kong Regional

Conference, **Urban Density & Sustainability**, 12 -13 September 2013; http://www.leedsmet.ac.uk/as/cebe/ [Accessed on 13th Sept 2013]
GORSE, C. SUTTON, R. JOHNSTON, D. MILES-SHENTON, D. and HOBDAY, J. (2011) Low Carbon Housing in the UK: Analysis of Construction Practice. Architecture Science, No.3, pp55-68.

GENTOO (2010) *A Retrofit Reality: A Dissemination Report by GENTOO. Part 2 of 3.* Available from http://www.sustainablehomes.co.uk/upload/news/Retrofit%20Reality%20part%202.pdf [Accessed 10th August 2011]

GOOD HOMES ALLIANCE, (2011) Good Homes Alliances: Standard, Available from http://www.goodhomes.org.uk/good-homes/standard [Accessed on 13th May 2011]

HMG (July 2009), *Transforming our power sector, The UK Low Carbon Transition Plan: National Strategy for Climate and Energy*. The Stationary Office. London

HMG (May 2010) *Approved Document L1A: Conservation of fuel and power (New dwellings) (2010 edition)* RIBA bookshops London

IBM (2007) SPSS 16 *SPSS 16.0 for windows*. Computer program IBM
JOHNSTON, D. MILES-SHENTON, D. WINGFIELD, J. FARMER, D. and BELL, M. (2012) Whole House Heat Loss Test Method (Coheating). A report for the IEA Energy Conservation in Buildings and Community Systems Programme Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurement. Leeds, UK, Centre for the Built Environment, Leeds Metropolitan University. http://www.leedsmet.ac.uk/as/cebe/ [Accessed on 13th Sept 2013]

KANNAN R AND STRACHAN N. (2009) *Modelling the UK residential energy sector under long-term decarbonisation scenarios: Comparison between energy systems and sectoral modelling approaches.* Applied Energy, Vol. 86 (4), Pg 416-428

LEAMAN, A, STEVENSON, F. AND BORDASS, B. (2010) *'Building evaluation: practice and principles'*, Building Research & Information, 38: 5, 564 — 577

LOWE, R.J., WINGFIELD, J., BELL, M., ROBERTS, D. & RIDLEY, I. (2008) *Parametric Domestic Energy Model – Version 15.94*, Leeds Metropolitan University, Leeds & UCL, London

LOWE, R.J., WINGFIELD, J., BELL, M. & BELL, J.M. (2007) *Evidence for significant heat losses through party wall cavities in load-bearing masonry construction* Building Services Engineering Research and Technology 28, 2, p161-181.

METEOROLOGICAL OFFICE, *Snow and low temperatures - December 2009 to January 2010* Available from http://www.metoffice.gov.uk/climate/uk/interesting/jan2010/ [Accessed 09th July 2010]

NATIONAL GRID (2010) Calorific value data obtained by request, Available from http://marketinformation.natgrid.co.uk/gas/DataItemExplorer.aspx [Accessed 08th June 2011]

NHBC (2009) Sustainability Extra Technical Newsletter No. 6, December 2009

ODPM (2006) *Building Regulations Approved Document L1A: Conservation of Fuel and Power in New Dwellings*. London: ODPM, Available from http://www.planningportal.gov.uk/england/professionals/en/1115314110382.html [Access 23rd July 2010]

Oreszczyn T. The energy duality of conservatory use. In: Proceedings of the third European conference on architecture: solar energy in architecture and planning, Florence, Italy, 17th–21st May; 1993.

OFGEM Fact Sheet 96: Typical domestic energy consumption figures, OFGEM, 18/01/11 Available from http://www.ofgem.gov.uk/Media/FactSheets/Documents1/domestic%20energy%20consump%20fig%20FS.pdf ; [Accessed 23rd May 2011]

OFFICE FOR NATIONAL STATISTICS, 2009, No.39 Social Trends, 2009 ed. Palgrave Macmillan

PALMITER, L.S. HAMILTON, L.B. & HOLTZ, M.J. (1979) *Low cost performance evaluation of passive solar buildings*, SERI/RR 63-223. Golden, Colorado: Solar Energy Research Institute.

ROBERTS, D., JOHNSTON, D. AND ISLE, J.A. (2005) *A Novel Approach to Achieving Airtightness in Dry-Lined Load-Bearing Masonry Dwellings*. Building Services Engineering Research and Technology Vol.26 [1] p.63-69

STEVENSON, F. & RIJAL, H. (2008) *Paper No 595: The Sigma Home: towards an authentic evaluation of a prototype building*. PLEA 2008 – 25th Conference on Passive and Low Energy Architecture, Dublin, 22nd to 24th October 2008

SUMMERFIELD, A.J. LOWE R.J. BRUHNS H.R. CAEIRO, J.A. STEADMAN J.P. AND ORESZCZYN T. (2007) *Milton Keynes▸ Energy Park revisited: Changes in internal temperatures and energy usage.* Energy and Buildings Volume 39, Issue 7, Pages 783-791

SUTTON, R. BELL, M. 2010; *Progress report, November 2010,* Leeds Metropolitan University

TECHNOLOGY STRATEGY BOARD, (2010) *Retrofit for the Future Competition for development contracts,* doc ref 209 201

TECHNOLOGY STRATEGY BOARD, (2010) *Competition: Building Performance Evaluation.* (Accessed http://www.innovateuk.org/content/competition/building-performance-evaluation-.ashx November 2010)

UTLEY, J.I. AND SHORROCK, L.D. (2006), *Domestic Energy Fact file: Owner occupied, Local Authority, Private rented and Registered social landlord homes*. BRE, London

WEATHER UNDERGROUND: (2010) Available from http://www.wunderground.com/cgi-bin/findweather/getForecast?query=Manchester,%20United%20Kingdom&wuSelect=WEATHER [Accessed 22nd April 2010]

BELL, M. WINGFIELD, J. MILES SHENTON, D. SEAVERS, J. (2010) Low carbon Housing: lessons from Elm Tree Mews Joseph Rowntree Foundation. Available from http://www.jrf.org.uk/publications/low-carbon-housing-elm-tree-mews

ZERO CARBON HUB (2009) *Defining a fabric efficiency standard for zero carbon homes.* ZCH London, Available from: http://www.zerocarbonhub.org/resources.aspx [Accessed 12th October 2010]

References: Stamford Brook Reports

LOWE, R.J. BELL, M. & ROBERTS, D. (2003) Developing Future UK Energy Performance Standards – St Nicholas Court Project Final Report, Leeds Metropolitan University, Leeds

ROBERTS, D. (2004) Evaluating the Impact of an Enhanced Energy Performance Standard on Load-Bearing Masonry Construction – Interim Report Number 3 Monitoring Plan, PII Project CI 39/3/663, Leeds Metropolitan University, Leeds

ROBERTS, D., BELL, M. & LOWE, R.J. (2004) Evaluating the Impact of an Enhanced Energy Performance Standard on Load-Bearing Masonry Construction – Interim Report Number 2 – Design Process, PII Project CI 39/3/663, Leeds Metropolitan University, Leeds

ROBERTS, D. ANDERSSON, M. LOWE, R.J. BELL, M. & WINGFIELD, J. (2005) Evaluating the Impact of an Enhanced Energy Performance Standard on Load-Bearing Masonry Construction – Interim Report Number 4 – Construction Process, PII Project CI 39/3/663, Leeds Metropolitan University, Leeds

ROBERTS, D., JOHNSTON, D. & ISLE, J. (2005) *A Novel Approach to Achieving Airtightness in Dry-lined Load-bearing Masonry Dwellings*, Building Services Engineering Research & Technology, Volume 26, Issue 1, pp 63-69

WINGFIELD, J. BELL, M. BELL, J. & LOWE, R.J. (2006) Evaluating the Impact of an Enhanced Energy Performance Standard on Load-Bearing Masonry Construction – Interim Report Number 5 – Post Construction Testing and Envelope Performance, PII Project CI 39/3/663, Leeds Metropolitan University, Leeds

WINGFIELD, J. BELL, J. BELL, M. & LOWE, R.J. (2006) Evaluating the Impact of an Enhanced Energy Performance Standard on Load-Bearing Masonry Construction – Interim Report Number 5a – Technical Note – Initial Results of Household Monitoring and Occupant Interviews, PII Project CI 39/3/663, Leeds Metropolitan University, Leeds

MILES-SHENTON, D., WINGFIELD, J. & BELL, M. (2007) Evaluating the Impact of an Enhanced Energy Performance Standard on Load-Bearing Masonry Construction – Interim Report Number 6 – Airtightness Monitoring, Qualitative Design and Construction Assessments, PII Project CI 39/3/663, Leeds Metropolitan University, Leeds

WINGFIELD, J., BELL, M., MILES-SHENTON, D., LOWE, R.J. & SOUTH, T. (2007) Evaluating the Impact of an Enhanced Energy Performance Standard on Load-Bearing Masonry Construction – Interim Report Number 7 – Co-heating Tests and Investigation of Party Wall Thermal Bypass, PII Project CI 39/3/663, Leeds Metropolitan University, Leeds

WINGFIELD, J., BELL, M., MILES-SHENTON, D., LOWE, R.J. & SOUTH, T. (2007) Evaluating the Impact of an Enhanced Energy Performance Standard on Load-Bearing Masonry Construction – Interim Report Number 8 – Final report, PII Project CI 39/3/663, Leeds Metropolitan University, Leeds

LOWE, R.J., WINGFIELD, J., BELL, M. & BELL, J.M. (2007) *Evidence for Heat Losses via Party Wall Cavities in Masonry Construction*, Building Services Engineering Research & Technology, Volume 28, Part 2, pp 161-181

All Stamford Brook reports are available at the Leeds Metropolitan University website at http://www.leedsmet.ac.uk/as/cebe/projects/stamford/index.htm

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Many thanks go to the participants, who agreed to be part of the research; especially those who helped with intensive monitoring.

We are extremely grateful to the meter readers, Ping and Jon, who collected meter readings each and every week, without fail, in spite of the weather, including thick snow; their dedication to the project has enabled a valuable dataset to be collected.

Thanks to the Trafford College for housing the weather station.

APPENDICES

Appendix A: Information Pack

Stamford Brook – An Exploration Of Energy Data

Information Sheet

We would like to invite you to participate in our energy data study at Stamford Brook. It is important that you are clear about what your participation will involve so that you are in a position to make an informed decision as to whether you wish to take part. This information sheet accompanies the householder consent form which should be completed and returned to the research team if you would like to take part.

GENERAL INFORMATION

Researchers at Leeds Metropolitan University are carrying out a research project to develop an understanding of building energy performance on the Stamford Brook Development and the best way to collect meaningful data from a large number of houses. Energy consumption differs from house to house and from family to family. It is important to understand these differences so that approaches can be developed to help households reduce consumption and bills. The research aims to develop practical solutions that help everyone to live comfortable lives while reducing energy use and carbon emissions. The information collected will be used to produce reports for publication.

Information relating to the methods of construction was collected in a previous research project. In this follow-up project we hope to carry out electricity and gas meter readings on around 100 homes and in a much smaller number measure internal temperatures and other factors. We would also ask households to fill in short questionnaires or take part in interviews so that we understand what occupants feel about their home and how they like to use it.

YOUR INVOLVEMENT

The following points describe what will happen if you agree to take part in the project.

We will take gas and electricity meter readings each week for about 12 months. This will not involve any disturbance to you because we will take the readings from the meters outside your house. Every time a meter reader calls they will pop a card through your door so that you know they have been and what the readings are. You will also be given a number to call if you have any queries.

At the beginning and at the end of the project we will also ask you to complete a short questionnaire to tell us about your household and any changes during the year so that we are able understand the energy readings.

In order to understand how energy is related to internal conditions in the home we will approach a number of households during the project to seek permission to collect data on such things as temperatures and humidity. Data collectors will be in the form of small sensors placed around the home in locations where they are unlikely to be disturbed. Additional testing and short interviews may be involved, if necessary. If you would be interested in this additional monitoring please let us know by ticking the appropriate box on the consent form.

CONTACT

During the research you may meet members of the research team from the University or locally recruited residents. Two residents of the Stamford Brook estate will be employed to collect the meter readings from the outside meters. This will not require access to your house.

With this information sheet you will find photographs and contact details of the University staff. Before your meter is read for the first time you will be told who your meter reader will be (including a photograph). All researchers will carry University ID cards and meter readers will have letters of identification with them at all times.

The monitoring arrangements have been designed so that we minimise the need to go into your house but if you have any queries please contact Ruth Sutton.

ANONYMITY

We will take all reasonable steps to preserve your anonymity and we will respect your privacy at all times. All personal data will be kept confidential and will be destroyed at the end of the project. When producing project reports and other publications based on the research, the data that we collect from your home will be presented in an anonymous form. This means that we will not provide any information that would identify your home, you or any member of your household.

We are bound by the terms of the Data Protection Act and unless you give your permission, we will not disclose any information we hold about you or your household to anyone outside the Leeds Metropolitan University research team. Your data will be held at the University and will be held securely.

At the end of the project you will be provided with a sheet telling you what your energy consumption has been over the monitoring period. You will also receive information on the average level of consumption across all the houses we monitored so that you can compare your consumption with the average. You will also receive information on where you can get hold of the final report when the project is finished.

The research is independent of the National Trust, Redrow and Taylor Wimpey and is funded through Government research funding. As such, no information regarding your participation will be passed to any external body. There will be no consequences to you if you chose not to take part.

WITHDRAWAL

We fully understand that you may change your mind about being involved in the project and would reassure you that, even if agree to take part, you are free to withdraw from the project at any time. If you feel it necessary to withdraw, all personal information will be deleted and if requested all research data relating to your house will be deleted also.

FURTHER INFORMATION

Thank you for your interest in the project. If you have any queries, please contact Ruth Sutton or one of the team at Leeds Metropolitan University.

Ruth Sutton

Research Assistant (Field Worker) – Energy & Sustainability

Appendix B: Questionnaire

Please find enclosed YOUR energy consumption questionnaire

As you will be aware, we have been collecting meter readings from your property on a weekly basis. The information collected will help us to measure how much energy you use in your home. However, as we explained at the beginning of the project, it is important that we understand how the amount of energy is affected by the number of people who live in your home and other aspects of use. To help us do this we are asking all participants to complete the enclosed questionnaire.

The questionnaire will take up to 20 minutes and asks for information about the people living in the dwelling, how you heat and cool your home and how you keep it fresh. There are questions about how your dwelling behaves and whether you feel your home responds to your choices.

Please answer all the questions as accurately as you can by providing information or ticking all boxes that apply. If there are any questions that you do not wish to answer then feel free to leave them blank. However, I would like to reassure you that the research is designed such that your privacy will be maintained at all times and no information will be presented that will enable you to be identified.

I would like to make it clear that you are under no obligation to complete this questionnaire. If you decide not to complete it this will not affect the rest of the research on your home and we will continue to take meter readings and feed back information to you.

I have attached a copy of the original information sheet. However, if you would like to discuss any thing relating to these or any other issues, please do not hesitate to contact me on 0113 812 9397.

Yours sincerely

Ruth Sutton

Research Assistant

Ref: ………………………..

To be completed by the research

ADDRESS…...……………………………………………………………………

………………………………………………………………………………

………………………………………………………………………………

…………………………………Postcode…………………………

Section A: This section contains question about your household. It will help the research team to understand when the house is occupied and by whom.

Household

1) How many adults live in the house? ……………………………………………
2) How many children live in the house? ………………………………………………….
3) What ages are the children? (please provide the number in each age group)

<5years...…… 6-10 years ……… 11-15years……….. 16-18years………..

Occupation Patterns

4) Considering a typical day, how many members of your of the household will be in the house during the following times?

	Weekdays (Mon-Fri)		Weekends (Sat & Sun)	
	Adults (over 18)	Children (0-18)	Adults (over 18)	Children (0-18)
Morning (4am-10am)	………..	………..	………..	………..
Daytime (10am-4pm)	………..	………..	………..	………..
Afternoon/ Evenings (4pm-10pm)	………..	………..	………..	………..
Night time (10pm-4am)	………..	………..	………..	………..

Section B: This section comprises questions about your house.

5) Have any changes been made to the home since moving in?... Yes / No*

If yes, then please tell us what work you've had done and who completed the work (contractor, developer, yourself).

……………………………………...………………………………………………………

……………………………………………………………………………………………

Section C: **In this section we ask you questions about how comfortable you feel in your home and how you adjust heating and other controls (eg. maintaining the right temperature and right amount of fresh air).**

Indoor temperatures

6) In general; during the **winter,** how would you describe the temperature of your home? Please indicate below.

Too Cold…☐	Cool…☐	Comfortable… ☐	Warm…☐	Too Hot …☐

7) In general; during the **summer**, how would you describe the temperature of your home? Please indicate below.

Too Cold…☐	Cool…☐	Comfortable… ☐	Warm…☐	Too Hot …☐

8) Are there any areas of your home in which you have difficulty maintaining comfortable conditions? …yes/no *

If so, please provide details:
....
....

Heating

These questions relate to how you operate the heating in your home. In these questions, please consider a "typical day".

9) Which of the following methods do you use to control the temperature of your home? (Please tick all that apply)

	Summer	Winter
I set the heating system timer	………	………
I turn the heating on and off as needed	………	………
I adjust the room thermostat	………	………
I adjust the Thermostatic Radiator Valves (TRVs)	………	………
I boost or reduce the ventilation system as necessary		
I open and close windows as needed	………	………
Other		

If other, please describe what you use……..…………………………..…………………….

.... …………………….

.... …………………….

10) Please tick below the periods when you would normally have the heating on during the **winter**.

	Weekdays (Mon-Fri)	Weekends (Sat & Sun)
Early Morning (approx. 6am-10am)	………………	……………………
Daytimes (approx 10am-4pm)	…………………	……………………
Afternoon/ Evenings (approx4pm-10pm)	…………………	……………………
Night times (approx. 10pm-6am)	……………………	………………

11) What temperature is your thermostat usually set to? ……….°C

12) How often do you adjust the household thermostat?

Daily …☐	Weekly …☐	Monthly … ☐	Never … ☐

13) How often do you adjust the thermostatic radiator valves (TRV's) around the home?

Daily …☐	Weekly …☐	Monthly … ☐	Never … ☐

14) Do you ever use any additional heating appliances to supplement the central heating; for example: electric fires, oil filled radiators, ...Yes /No*

If yes, please describe what you use ………..…………………………...…………………….

.... ………………

.... ………………..

15) When considering your heating bills, how does the cost of heating your home compare to your previous home?

Lower …☐	About the same …☐	Higher …☐	Don't know …☐

Ventilation

These questions relate to how you keep the air fresh in your property. In these questions, please consider a "typical day".

16) Which of the following methods do you use to control fresh air levels in the home? (Please tick all that apply)

	Summer	**Winter**
Mechanical ventilation system	…………………….	………………….
Opening windows	…………………….	………………….
Neither	……………………….	………………….

17) Do you use any additional equipment to keep you cool in summer? For example; a portable air conditioner, fans etc.? ... Yes /No*

If yes, please provide details…..

Section C: Understanding how your home works

Please score on a scale of 1 to 3 how well you feel that you understand the features in your home and how they can be used to improve your comfort.

18) How well do you feel that you understand how the heating system works?

1 (I find it difficult to work the system) ☐	**2** (I understand the basic features) ☐	**3** (I feel able to use all features) ☐

19) How well do you feel you understand how the mechanical ventilation system works?

1 (I find it difficult to work the system) ☐	**2** (I understand the basic features) ☐	**3** (I feel able to use all features) ☐

Section D: Other

These questions will help the research team gain an overall view of how you feel your home performs. There is also the opportunity for you to elaborate further on any other aspect of the energy performance of your property.

20) Overall, how would you rate this property in terms of the general comfort following: heating, ventilation, comfort? Where 1 represents very poor and 3 represent very good.

1 (Very Uncomfortable) ☐	**2** (Comfortable) ☐	**3** (Very Comfortable) ☐

21) Overall, how would you rate this property in terms of ease of use?

1 (very easy to use) ☐	**2** (easy to use) ☐	**3** (manageable) ☐	**4** (difficult to use) ☐	**5** (very difficult to use) ☐

22) Are there any aspects of the property that you would change (if the cost was not an issue)? Please give your reason.

....

....

....

23) Have you any comments relating to the above questions or any other aspect of energy use in your home?

………………..

Please return completed forms in the Freepost envelope enclosed to:

Ruth Sutton,
Centre for the Built Environment,
Leeds Metropolitan University,
Civic Quarter,
Leeds, LS1 3HE.

Many thanks for your help.

Appendix C: Summary of Participating households

A: Extensive Monitoring

House design	**No. of participating Dwellings**	**Floor Area**	**Storey**	**House form**
Apartment: bespoke	10	Assumed to be 66	1	--
Apartment: Whittle Eleveden	5	66	1	--
Calder (CAE)	3	70	1	Apartment
Avon (AVO)	2	131	2.5	semi detached
Charlebury (CBY)	3	92	3	2 end terrace, 1 mid terrace
Chatsworth (CHW)	12	72	2	1 detached, 2 mid terrace, 9 end terrace
Castleton (CS)	3	165	2	2 detached 1 semi detached
Derwent (DER)	9	123	2.5	5 mid terrace 4 end terrace
Devoke (DEV)	4	84	2	1 mid terrace 3 end terrace
Fern (FER)	2	63	2	3 detached
Fyne (1,4) (FYN)	3	89	2	3 mid terrace
Romsey (ROM)	2	131	2	2 detached
Mendip (MEN)	2	159	3	2 mid terrace
Monarch (MON-A)	2	105	3	2 end terrace
Tweed (1,2) (TW)	2	185	2.5	1 semi detached 1 detached
Wye (WY)	2	105	3	2 end terrace
XT (1,2,3)	6	137	2.5	1 mid terrace 2 semidetached 2 end terrace
Doniford (DOF)	1	91	2	1 mid terrace 1 end terrace
Cliveden (CL)	1	189	2	1 detached
Foss (FO),	1	146	2.5	1 detached
Grannoch GR),	1	87	2	End terrace
Llanberis (LL)	1	89	2	Mid Terrace
B.RA,	1	91	2	End Terrace
Conway (CON)	1	150	2	Semi detached

Mah,	1	120	2	Mid Terrace
RGH,	1	137	3	Semi detached
Fa(h)	1	70	2	End terrace

Appendix D: All pressurisation test results

Test Date	**Plot test ref.**	**Developer Design Type (Phase)**	**Dwelling Form**	**Permeability (m/h)**	**Volumetric ACH**	**R^2 Coefficient**	
						Depress	**Press**
23-Feb-05	1	Chatsworth (1)	2-storey Semi	3.32	3.67	0.992	0.998
23-Feb-05	2	Chatsworth (1)	2-storey Semi	2.04	2.26	0.988	0.999
01-Apr-05	3	Devoke (1)	2-storey End Terrace	3.67	3.82	0.995	0.967
01-Apr-05	4	Whittle (1)	Ground Floor Flat	1.75	2.46	0.987	0.992
04-Apr-05	5	Derwent (1)	2 ½ -storey Mid Terrace	6.09	5.51	1.000	0.999
26-Apr-05	6	Fyne (1)	2-storey Mid Terrace	2.98	2.92	0.995	0.987
04-May-05	7	Devoke (1)	2-storey End Terrace	4.64	4.83	0.994	0.99
04-May-05	8	Devoke (1)	2-storey End Terrace	4.78	4.87	0.994	0.999
04-May-05	9	Doniford (1)	2-storey Semi	4.67	4.73	0.997	1.000
12-May-05	10	Derwent (1)	2 ½ -storey Mid Terrace	7.02	6.35	0.987	0.985
12-May-05	11	Chatsworth (1)	2-storey Semi	4.66	5.15	0.994	0.998
12-May-05	12	Type G (1)	2-storey Detached	3.23	2.8	0.998	0.993
20-May-05	130	Devoke (1)	2-storey End Terrace	3.19	3.32	0.988	0.999
05-Oct-05	14	Wye (1)	3-storey End Terrace	5.89	5.5	0.998	0.999
01-Nov-05	15	Devoke (1)	2-storey Mid Terrace	3.81	3.97	1.000	0.992
16-Nov-05	16	Castletown (1)	2-storey Detached	2.91	2.94	0.996	1.000
21-Nov-05	17	Wye (1)	3-storey End Terrace	4.64	4.34	1.000	1.000

01-Dec-05	18	Cliveden (1)	2-storey Detached	3.46	3.03	0.972	0.989
07-Dec-05	19	Mendip (1)	3-storey End Terrace	4.85	4.2	0.999	0.999
09-Dec-05	20	Balmoral (1)	3-storey Mid Terrace	4.41	3.75	0.999	0.995
09-Jan-06	21	Wye (1)	3-storey Mid Terrace	5.28	4.94	1.000	0.998
24-Jan-06	22	Derwent (1)	2 ½ -storey Mid Terrace	7.44	6.44	0.999	0.997
25-Jan-06	23	Dunham (1)	2 ½ -storey Mid Terrace	9.7	8.41	0.999	0.981
27-Jan-06	24	Derwent (1)	2 ½ -storey Mid Terrace	7.79	7.05	0.996	0.997
15-Feb-06	25	Balmoral (1)	3-storey End Terrace	5.75	4.89	0.979	0.986
16-Feb-06	26	Whittle (1)	Ground Floor Flat	3.61	5.2	0.99	0.996
17-Feb-06	27	Wye (1)	3-storey Mid Terrace	6.3	5.9	0.999	0.998
08-Mar-06	28	KE (1)	Top Floor Flat	6.62	9.45	0.999	0.995
23-Mar-06	29	Tweed (1)	2 ½ -storey Detached	6.21	4.86	0.998	0.993
05-Apr-06	30	Romsey (1)	2-storey Detached	6.08	5.8	0.98	0.994
07-Apr-06	31	Tweed (1)	2 ½ -storey Detached	5.97	4.68	0.995	0.994
08-Oct-09	A1	APT (1)	Ground floor flat	6.01	8.64	0.999	0.999
07-Apr-10	A2	Derwent (1)	2.5 storey semi-detached	3.72	3.38	0.996	0.998
10-Jun-09	A4	Derwent (1)	2.5 storey end terrace	6.83	6.47	0.994	0.996
17-Jun-09	A5	Derwent (2)	2.5 storey end terrace	7.3	6.92	0.996	1.000
17-Jun-09	A6	Derwent (1)	2.5 storey end terrace	10.54	9.98	1.000	0.988
07-Apr-10	A8	Devoke (1)	2 storey end terrace	5.87	6.14	0.999	0.998
17-Jun-09	A9	Devoke (2)	2 storey end terrace	8.08	8.45	0.992	0.996
12-May-10	A10	Devoke (2)	2 storey end terrace	8.5	9.63	0.995	0.995
12-May-10	A11	Romsey (1)	2 storey Detached	6.08	5.8	0.993	0.995
06-Oct-09	A13	Wye (1)	3 storey end terrace	4.71	4.4	0.998	0.997

02-Jun-10	A15	XT2 (1)	2.5 storey end terrace	6.27	5.43	0.997	0.996

Appendix E: Test equipment

Component	Equipment Used	Equipment Specification
Meter reading equipment		
Netbook for recording meter readings	Samsung NP-NC10	1 per meter reader
Household monitoring equipment		
Internal Temperature/Humidity Sensor	Tinytag Ultra 2: TGU-4500 Dual Channel Temperature/Relative Humidity datalogger (-25 to +85°C/0 to 95% RH)	3 per dwelling in kitchen, living room, master bedroom Or 1 per dwelling in kitchen, living room or bedroom
CO_2 Sensor	Vaisala GM22 CO_2 Transmitter with power supply plus Tinytag TGPR0804	1 per dwelling in master bedroom Maximum reading 2000ppm
Weather station		
Logger and modem	Eltek RX250 data logger and modem	Located within the building and connected to a power supply. Modem connected to a network to enable off site data downloading.
External Temperature/Humidity Gauge	Rotronic Hygroclip S3 External Temperature/Humidity Sensor	Positioned at 2m on 4m mast Protected by Stephenson Radiation Screen
External Temperature/Humidity Transmitter	Eltek GS-13 Hydroclip Radio Transmitter	Located in weather proof box on mast
Pyranometer	Kipp & Sonnen CM3 Pyranometer	Vertical & horizontal orientations South Facing Positioned at 3m on 4m mast
Pyranometer Transmitter	Eltek GS-42 Voltage Radio Transmitter	Located in weather proof box on mast
Anemometer 1	Schiltknecht Meteo Anemometer/Wind Vane	Positioned at 4m on 4m mast Instantaneous wind speed in m/s
Anemometer 1 Transmitter	Eltek GS-42 Voltage Radio Transmitter	Located in weather proof box on mast
Anemometer 2	Vector Instruments AN1 Anemometer	Positioned at 4m on 4m mast Mean wind speed in m/s over the 10 minute logging period
Anemometer 2 Transmitter	Eltek GS-62 Pulse Radio Transmitter	Located in weather proof box on mast

Appendix F: Calculation of mean internal temperature.

1. Up to three temperature data loggers were installed into the dwellings participating in the additional monitoring. Where possible loggers were installed at approximately 1.5m. Care was taken to avoid placing the logger in direct sunlight or next to heat sources.
2. Where possible the loggers were placed in the kitchen, the lounge and the bedroom, in order to give a broad understanding of temperature variation across the dwelling.
3. In order to determine zones the following conventions were met:
4. Zone 1: The lounge represented only one zone and the area was calculated as the area of the lounge.
5. Zone 2: The kitchen zone included areas of hall, landing and toilets of the same floor.
6. Zone 3: The temperature in the bedroom was indicative of all bedrooms, stairs and bathrooms on that level unless another tiny tag was also used.
7. All floor area was accounted for in the calculation.
8. Mean daily temperature was used instead of the mean temperature during the time the heating system was on. This may have reduced the lowered the mean temperature but is necessary as solar gains and all electrical gains are included in the SAP assessment.

Appendix G: Internal monitoring results

Average house temperature

House code *	Jun-09	Jul-09	Aug-09	Sep-09	Oct-09	Nov-09	Dec-09	Jan-10	Feb-10	Mar-10	Apr-10	May-10
A8 (3)		24.6	24.8	21.5	19.9	19.3	19.5	19.2	19.4	20.5	20.9	21.4
A9(3)	21.3	22.4	22.0	19.9	19.5	17.7	17.8	17.6	18.5	18.4	19.9	18.9
A4 (3)	21.3	21.3	20.9	19.7	19.6	18.6	17.8	17.7	17.9	18.5	19.0	16.5
A5 (3)	24.9	23.1	22.5	20.7	18.0	16.3	15.1	15.0	16.2	17.5	17.5	
A6 (3)	24.8	23.7	23.7	21.2	20.8	19.6	19.5	18.3	19.0	20.0	20.6	18.2
A7 (3)		21.7	21.9	19.6	19.1	19.8	18.2	17.5	18.6	19.7	19.5	20.1
A11 (3)	23.3	22.3	22.6	21.9	19.3	16.8	15.7	14.6	15.8	17.2	17.0	17.8
A12 (1)		20.8	21.2	20.3	20.0	19.1	17.9	16.6	19.0	19.4	19.1	19.7
A13 (3)					19.4	19.0	18.4	19.3	18.9	20.0	20.3	20.6
A3 (3)	24.6	24.5	23.3	22.3	21.0	20.0	19.3	18.8	17.3	19.4	19.8	19.6
A2 (1)			21.1	20.7	20.4	19.9	15.1	16.3	19.3	20.1	19.9	19.5
A15 (3)	19.0	18.2	18.3	17.1	16.1	15.7	14.9	15.3	14.9	15.7	14.5	15.6
A10 (1)		23.2	24.1	22.3	21.8	20.3	19.9	18.8	19.6	20.2	20.0	19.9
A14 (1)		25.5	24.0	23.1	20.9	20.2	19.4	18.5	17.5	16.8	20.0	18.1
A1(3)					21.1	22.6	22.1	22.9	22.5	22.1	21.8	

Average house relative humidity

House code	Jun-09	Jul-09	Aug-09	Sep-09	Oct-09	Nov-09	Dec-09	Jan-10	Feb-10	Mar-10	Apr-10	May-10
A8 (3)		12.0	12.3	10.6	9.8	8.7	7.3	6.7	7.1	7.6	7.9	8.3

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* The number in brackets indicates the number of sensors in the dwelling.

A9(3)	**10.6**	**11.7**	**11.9**	**10.8**	**11.1**	**9.2**	**8.3**	**7.1**	**7.3**	**7.3**	**8.2**	**7.9**
A4 (3)	**10.2**	**10.8**	**11.0**	**10.8**	**11.2**	**9.9**	**9.3**	**8.7**	**8.4**	**8.7**	**8.1**	**6.0**
A5 (3)	**13.7**	**12.1**	**12.2**	**11.0**	**9.8**	**9.0**	**7.4**	**6.7**	**7.0**	**7.6**	**8.2**	
A6 (3)	**12.6**	**11.9**	**12.3**	**11.0**	**9.9**	**7.6**	**6.6**	**5.6**	**7.4**	**7.8**	**8.4**	**6.7**
A7 (3)		**11.2**	**11.6**	**10.3**	**9.7**	**9.1**	**7.6**	**6.5**	**6.4**	**6.8**	**7.7**	**8.2**
A11 (3)	**12.3**	**11.2**	**11.7**	**10.5**	**9.2**	**8.5**	**7.4**	**6.3**	**6.8**	**7.4**	**7.4**	**7.5**
A12 (1)		**11.5**	**11.9**	**11.1**	**10.6**	**9.8**	**8.4**	**7.1**	**8.0**	**8.2**	**8.0**	**8.3**
A13 (3)					**10.2**	**9.7**	**8.6**	**7.9**	**7.8**	**8.3**	**8.7**	**9.0**
A3 (3)	**12.9**	**11.8**	**11.8**	**11.1**	**10.2**	**9.0**	**7.9**	**7.2**	**6.7**	**7.6**	**8.1**	**8.1**
A2 (1)			**12.3**	**12.0**	**11.1**	**10.1**	**6.7**	**6.9**	**7.6**	**7.9**	**8.5**	**9.0**
A15 (3)	**6.8**	**6.5**	**6.5**	**6.1**	**6.1**	**5.8**	**5.0**	**4.6**	**4.5**	**4.7**	**4.4**	**4.7**
A10 (1)		**11.3**	**11.8**	**10.4**	**9.6**	**9.3**	**7.9**	**6.2**	**6.6**	**6.9**	**7.2**	**7.4**
A114 (1)		**11.7**	**11.4**	**11.1**	**9.5**	**8.5**	**6.7**	**5.5**	**5.5**	**5.3**	**6.8**	
A1(3)					**10.0**	**11.1**	**10.5**	**9.1**	**9.2**	**9.0**	**9.5**	
External absolute humidity	**9.4**	**10.7**	**10.9**	**9.6**	**8.6**	**7.3**	**5.5**	**4.1**	**5.2**	**4.9**	**6.4**	

Appendix H: Co-heating test locations

Plot No.	**House Form**	**GFA (m2)**	**Test Date**	**Comment**
13	2-storey Semi-detached	73	Dec 2005	Show house
402	3-storey Mid-terrace	106	Jan 2006-Feb 2006	-
116	2-storey Semi-detached	73	Jan 2007-Feb 2007	Same type as plot 13, Adjacent to 117
117	2-storey Semi-detached	73	Jan 2007-Feb 2007	Same type as plot 13, Adjacent to 116
110	3-storey Mid-Terrace	137	Feb 2007-Mar 2007	Adjacent to 111
111	3-storey End-Terrace	141	Feb 2007-Mar 2007	Adjacent to 110

Appendix I: Glossary

BRE: The Building Research Establishment is an organisation involved in research into various aspects of the built environment, including energy performance of buildings etc.

BREDEM: Building Research Establishment Domestic Energy Model, A tool created by the BRE for use in calculating the energy use of a domestic building.

Degree day: A measurement of the difference between daily external temperature and a predetermined external temperature at which a building required no additional space heating or cooling to achieve thermal comfort. Often used to estimate space heating demand.

Heat loss coefficient: A heat loss coefficient represents the heat loss of a building per degree Kelvin difference between internal and external temperature represented by the unit **W/K**

Heat loss parameter: represents the heat loss of a building per degree Kelvin difference between internal and external temperature per unit of floor area. Represented by the unit **W/m^{2}K** (Not to be confused with U-value, though they both share the same unit)

OFGEM: The Office of Gas and Electricity Markets, the UK regulator that governs the energy industry within the UK. Also provides industry statistical information.

SAP: Standard Assessment Procedure, the standard assessment method adopted by the UK government for calculating the energy use and environmental impact of a building.

Thermal Bridging: Thermal bridging is the result of the penetration or "bridging" of a thermally insulating layer by a material of higher thermal conductivity than the material it penetrates. Thermal bridging can drastically reduce the thermal efficiency of a building's fabric due to the bypassing of any insulating layers.

U-value: A U-value represents the rate at which thermal energy is transmitted through a barrier per unit of area, per degree of temperature difference. Represented by the unit **W/m^{2}K**

Units:

kgCO$_2$/kWh: the measure of the mass of carbon dioxide produced by energy use. Expressed as the number of **kilograms (kg)** of **carbon dioxide (CO$_2$)** per **kilowatt hour (kWh)** of energy used

kWh/a: A measure of energy used over the period of a year. Expressed as **kilowatt hours (kWh)** used per **Annum (a)**

kWh/m^2.a or (kWh/m^2)a: The unit representing the average energy used per unit of floor area in a building. Expressed as **kilowatt hours (kWh)** of energy used per **square metre (m^2)** of a building per **annum (a)**

m^3/(h.m^2) @ 50 Pa: The air permeability of a building. Expressed as **volume of air (m^3)** lost per **hour (h)** per **square metre (m^2)** of exposed building exterior at an air pressure differential of 50 **pascals (Pa)**

MJ/m^3: A measure of energy density, expressed as the amount of energy; **megajoules (MJ)** per **cubic metre (m^3)** of a given substance (in this case combustible gas)

W/K: The unit representing a building's heat loss coefficient. Expressed as the energy in **watts (W)** lost by the whole building per degree **Kelvin (K)** difference in internal and external temperatures.

W/m^{2}K (Heat Loss Parameter)**:** Represents the number of **Watts (W)** heat lost per square metre **(m^2)** floor area per degree **Kelvin (K)** temperature difference between internal and external temperature of a building.

W/m^{2}K (U-Value)**:** The unit that U-values (thermal transmittance) are measured in. The unit represents the number of **Watts (W)** transmitted per square metre **(m^2)** per degree **Kelvin (K)** temperature difference either side of a barrier.