Centenary Quay

Phase 2 study
In-use and post-occupancy

This document contains a Building Performance Evaluation report from the £8 million Building Performance Evaluation research programme funded by the Department of Business Innovation and Skills between 2010 and 2015. The report was originally published by InnovateUK and made available for public use via the building data exchange website hosted by InnovateUK until 2019. This website is now hosting the BPE reports as a research archive. As such, no support or further information on the reports are available from the host. However, further information may be available from the original InnovateUK project evaluator using the link below[1].

Innovate UK project number	450077 Related CHP study: 450078 (Phase 1)
Project author	UCL and Crest Nicholson Operations for Crest Nicholson Plc
Report date	2014
[1]InnovateUK Evaluator	N/A

No of dwellings	**Location**	**Type**	**Constructed**
Three	Woolston, Hants	3-storey terraced houses	2012

Areas	**Construction form**	**Space heating targets**	**Certification level**
103.3 m^2	Cavity masonry	See report	Building Regulations, 2006

Background to evaluation

This report provides the results of the in-use performance analysis and post-occupancy evaluation of three monitored dwellings constructed as part of the first phase of Centenary Quay development. The performance of the district heating system and the CHP plant installed was assessed as part of the Phase 1 study.

Design energy assessment	**In-use energy assessment**	**Sub-system breakdown**
Yes (SAP)	Yes	Yes

Temperatures recorded for the monitored dwellings show higher risk of overheating than predicted in the as-built *Building Regulations* compliance calculations (as-built SAP). All bedrooms in one dwelling and the second floor bedroom in all dwellings experienced overheating during the measurement period. The operational performance of the district heating system and the combined heat and power plant was disappointing with respect to overall energy centre efficiency, system power-to-heat ratio and heat distribution efficiency. The carbon intensity of delivered heat at Centenary Quay was also more than double what would be expected from individual gas-fired condensing boilers. CO_2 concentrations in most liveable spaces were lower than 1500 ppm for more than 90% of the monitoring time. Measurements of low extract rates in all monitored dwellings suggested that the mechanical ventilation systems failed to deliver their designed performance.

Occupant survey type	**Survey sample**	**Structured interview**
BUS domestic	24 of 168 (14 % response rate)	Yes

Note: BUS report not included and hyperlink now defunct. Interviews carried out with the residents in the monitored mid-terraced houses showed overall, satisfaction with the new homes. They particularly like the design, layout and space the houses provided. They were also generally content with the indoor thermal comfort conditions, although gender differences in perceived thermal comfort were found. Residents in two monitored dwellings raised concerns about high heating bills. Window trickle vents were found permanently blocked in two dwellings with paper blinds and closed in another dwelling in winter to prevent draught.

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Executive Summary

This report provides the results of the in-use performance analysis and post-occupancy evaluation of three monitored dwellings constructed as part of the first phase of Centenary Quay development at Woolston near Southampton. The performance of the district heating system and the CHP plant installed for the development was assessed as part of the Phase 1 TSB study: Centenary Quay Fabric and District heating Performance Study 450078. It is also discussed in this report to contextualise and provide insight in support of some of the findings of the ongoing monitoring and customer feedback. Phase one of the project covered post-construction and early occupation.

The interviews carried out with the residents in the monitored mid-terraced houses showed that, overall, the residents are very satisfied with their new homes. They particularly like the design, layout and space the houses provide. They were also generally content with the indoor thermal comfort conditions, although notable gender difference in perceived thermal comfort was observed. However, there were a few discrepancies between dwellings' actual performance and residents' expectation. For example, residents in two monitored dwellings raised concerns about their heating bills, which they thought were higher than what they would have expected from their new build homes.

One of the major findings of the interviews was that the trickle vents on window frames were permanently blocked in two dwellings with paper blinds and closed in another dwelling in winter to prevent draught. It is recommended that the critical role of trickle vents in maintaining good indoor air quality in new build dwellings is more specifically covered in home user guides and home demonstration in the future.

The monitoring results showed the thermal comfort conditions in winter in occupied spaces were within the acceptable limits defined by guidelines. The CO_2 concentrations in most liveable spaces were lower than 1500 ppm for more than 90% of the monitoring time. This limit for CO_2 concentrations is a good proxy for good indoor air quality. Maximum CO_2 concentration recorded in the monitored dwellings was 3,850 ppm in one of the bedrooms. Effective use of the trickle vents could help reduce the peak CO_2 concentration levels that often occur in winter.

The disaggregated heating and electricity consumption shows differences in usage patterns between the three monitored dwellings as shown in the following table. The energy consumption associated with space heating shows the effectiveness of insulation and airtightness in achieving good performance when dwellings' performance is compared against the typical existing building stock.

Delivered energy (kWh/m²/annum)	Best Practice Benchmark	Typical Benchmark	Plot 118	Plot 119	Plot 120
Space Heating	28.1	132.8	42.1	39.2	13.8
Domestic Hot Water	9.2	43.3	12.8	70.3	14.6
Cooking	3.6	6.6	5.3	10.1	9.6
Lighting	1.3	6.8	2.0	4.9	1.0
Appliances	9.8	28.99	6.6	9.6	3.0
Auxiliary Energy (fans and pumps)	0.4	2.0	0.3	2.1	0.3

Three key messages come out of this report that could be of interest to policy makers, developers, designers, contractors and other stakeholders in the construction industry:

Overheating risk in new build dwellings:
Temperatures recorded for the monitored dwellings show higher risk of overheating than what was predicted in the as-built Building Regulations compliance calculations (as-built SAP). Furthermore, according to the overheating procedure detailed in CIBSE Guide A, all bedrooms in one dwelling and the second floor bedroom in all dwellings experienced overheating for a proportion of time during the measurement period. While the CIBSE Guide A procedure is the most relevant method for overheating assessment currently used with more stringent criteria than the regulatory procedure, it should be noted that the feedback received from the occupants in the monitored dwellings does not suggest that overheating is a serious issue at present. Furthermore, the interviews revealed that there was a clear gender difference in perceived thermal comfort, which is not taken into account in CIBSE overheating procedure and other overheating methods currently used in the industry.

Despite the shortcomings of existing methods for overheating analysis, the in-use performance data suggest that the monitored dwellings at Centenary Quay could be at risk of serious overheating when subject to high external temperatures expected as a result of climate change over the coming years. Therefore, it is important to start thinking about measures that could help reduce the risk of overheating.

At dwelling level, it is recommended that occupants are advised about practical ways of reducing the risk of overheating. This can include simple recommendations, such as managing internal heat gains associated with appliances and lighting, night time ventilation in summer, applying solar film on the windows, effective shades or external blinds, and turning off the keep-hot facility in the Heat Interface Units (HIUs). At community level, measures that could help reduce the risk of overheating include reducing the district heating flow temperature or turning off the communal heating when external temperatures are high; all of which could be discussed with the operator of the district heating system. It should be noted that the risk of overheating is likely to increase in the future with the rises in seasonal atmospheric temperature that may result from climate change. Therefore, informing the residents and operators about the potential risks and practical ways of mitigating these in the future could be viewed as good practice to go beyond minimum regulatory requirements and enhance the resilience of the development to overheating.

As for future projects, it is recommended that overheating assessment procedures that are more stringent and robust than the existing regulatory procedure within the Standard Assessment Procedure are used. More robust assessments could assess the risk of overheating if the dwelling is subject to extreme weather conditions experienced in the past, and also the effect of future climate change scenarios. In part as a result of this project and other work across the business, Crest Nicholson has put in place a robust process to assess the potential of overheating in its dwellings, and mitigate it where necessary. The details of the process are outlined in Section 7.8.

Finally, it is vitally important to take into account the trade-offs between energy efficiency and air exchange in building design to ensure measures designed to increase energy efficiency do not compromise the overheating performance of the building.

The issue of overheating is one faced by the entire new build housing sector as requirements for increased thermal performance of homes must be balanced against the need to build homes that can adequately respond to the anticipated possible effects of climate variation and extreme weather conditions. Finding this balance is further challenged by the current inadequacy of tools and data available to developers and design teams for estimating and designing to manage overheating potential.

Performance of Mechanical Extract Ventilation (MEV) systems:

Measurements of low extract rates from the mechanical ventilation ductwork in all monitored dwellings suggest that the MEV systems have failed to deliver their designed performance. The consequence of this is that the air quality in some dwellings may not be as good as expected and that there could be longer term issues with condensation and mould growth. The underperformance of the MEV system may also contribute to overheating.

These problems could be attributed to a mixture of issues such as poor installation practice, inadequate commissioning processes, and a general lack of understanding about the important influence that mechanical ventilation systems can have on performance. It is envisaged that the requirement of providing mechanical ventilation system commissioning certificates, introduced in Part F 2010, would help improve the commissioning process. Shortcomings in fan, ductwork and terminal installation could have a severe impact on specific fan powers and extract rates. It is necessary to ensure the installation of the system is in accordance with the design intent in future projects. As for the existing installation in the monitored dwellings, introducing an over-run function and humidistat control in the wet rooms could help by ensuring that the boost mode is operated for long enough to clear moisture.

Crest Nicholson has introduced several measures to respond to the issues highlighted in Phase I and II of this project relating to installation and commission of MEV systems, as well as other areas. These measures are detailed in Section 4.2.

Performance of district heating:

A review of the operational performance of the district heating (DH) system and Combined Heat and Power (CHP) plant showed that the performance of the system over the period

October 2012 to July 2013 was disappointing with respect to three key parameters: overall energy centre efficiency, system power to heat ratio and heat distribution efficiency.

These factors combined mean that the carbon intensity of delivered heat at Centenary Quay is more than double what would be expected from individual gas-fired condensing boilers. This estimate is subject to a number of uncertainties, which are discussed throughout the report. A key source of uncertainty stemmed from difficulties in accessing basic performance data. These difficulties almost certainly have made the job of the E.ON. team (who were not involved in the initial design of the scheme and is tasked with managing and optimising the performance of this complex system) more difficult than it needed to be. In our view, this is a partial explanation for the disappointing performance of the scheme up to this point. Further degradation of performance may have resulted from mismatches between heat load and CHP/DH system capacity, and disturbances to normal operation that are hard to avoid during an on-going development project. Therefore, we do not believe that the findings presented here are necessarily a good indicator of the long-term performance and true potential of the system.

In our view, complexity, coupled with the relative lack of experience with such systems in the UK, makes it almost inconceivable that full performance could be achieved without a lengthy period of “sea trials”. But the reverse side of the complexity of a CHP/DH system is that it should be possible to achieve significant overall improvements in performance once under-performance and its causes have been made visible.

Across 2013 improvements have been made to improve the operational performance of the CHP/DH system. These include:

- Improving the control system logic to ensure the CHP engine operates at an optimum heat and electrical output.
- Improving the system to ensure heat is delivered from the energy centre and not lost within the energy centre due to mixing in the thermal store.
- Adjusting district heating flow and return temperatures to reduce distribution losses.
- Identifying and replacing possible areas of missing or defective insulation to pipework.
- Improvements in metering to ensure accuracy, including the addition of further heat meters to better understand network behaviour.

A crucial area for attention is likely to be IT support for real time performance visualisation to support operation and longer term planning. It is recommended that further assessments are carried out to establish to what extent these measures have been able to improve the performance of the DH system and CHP plant.

One of the key lessons learned for the future projects is that it is vital to choose an experienced contractor to deliver the district heating system who can take responsibility for the design, installation, commissioning and management of the system.

There is an increasing tendency to specify district heating for large new housing developments due to the huge potential of these schemes for reducing CO_2 emissions. However, it is vitally important to have a better understanding of the risks associated with these schemes and improve their operational performance. A requirement for ESCOs to publish operational data could be a good incentive to improve performance and also provide data for further research about the effectiveness of these schemes in the future.

1 Introduction and overview

Technology Strategy Board guidance on section requirements:	This section of the report should be an introduction to the scope of the BPE project, the expected results and will include a summary of the key facts, figures and findings. Give an introduction to the project covering the project team and a broad overview of the energy strategy, design strategy rationale and soft and hard monitoring. Also summarise the building type, form, materials, surrounding environment and orientation, as well as related dwellings in the development (which may or may not be part of the BPE project). Other amenities, such as transport links, cycling facilities, etc. should also be outlined where relevant. Give information on any environmental requirements issues that are relevant to the site, but not to the research. Only the basic facts etc. should be included here - more detailed information should be given in the relevant sections in this document and added to the data storage system as appropriate.

This report provides an overview of the major findings of Phase 2 of the Building Performance Evaluation project for Crest Nicholson's Centenary Quay development. Phase 2 explored the in-use performance and post-occupancy evaluation of 3 monitored dwellings along with analysing the performance of the district heating system and CHP plant at the development.

Sections 2-4 and Section 6 of the report summarise the key findings of Phase 1 and the conclusions drawn that are most relevant to Phase 2.

Sections 5 and 7 provide a detailed account of the findings of Phase 2. Section 5 includes the results of the second round of interviews with the occupants in the monitored dwellings. Section 7 details the findings of the monitoring programme and the review of the district heating system and CHP plant.

Finally, Sections 8 and 9 of the report outline the key lessons learned from both phases of the project with special focus on in-use performance.

The performance in-use and post occupancy evaluation were focused on three mid-terraced houses completed in 2012 as part of the first phase of the Centenary Quay development at Woolston near Southampton. Centenary Quay is a large scale regeneration project on land formerly part of the Vosper Thorneycroft shipyard which closed in 2004 (see Figure 1 which shows the site of the original shipyard prior to demolition).

Figure 1 - Birdseye view of area of Centenary Quay development (outlined in red)

The land was initially acquired by the South East England Development Agency (SEEDA) and comprises a 17.5 hectares bordered by a traditional local district centre of retail and commercial uses on Victoria Road to the north, an existing residential area to the east, the River Itchen to the west and a sewerage treatment works to the south. The scheme is mixed-use, and includes non-residential buildings for retail, offices, hotel, community facilities, and light industrial and marine-related manufacturing units together with 1,620 homes. Crest Nicholson Regeneration were appointed as the scheme developers in 2006. The first phase of the Centenary Quay project comprises 168 dwellings formed of several terraces of town houses and apartment blocks, together with construction of the first of the two energy centres and its associated heating network (see Figure 2). The majority of physical measurements undertaken at Centenary Quay were carried out on houses that formed part of a terrace block in Phase 1 (see Figure 2). This block was constructed during 2012 and was the last of Phase 1 to be completed. The performance in-use and post-occupancy evaluation were focused on three mid-terraced houses in this block.

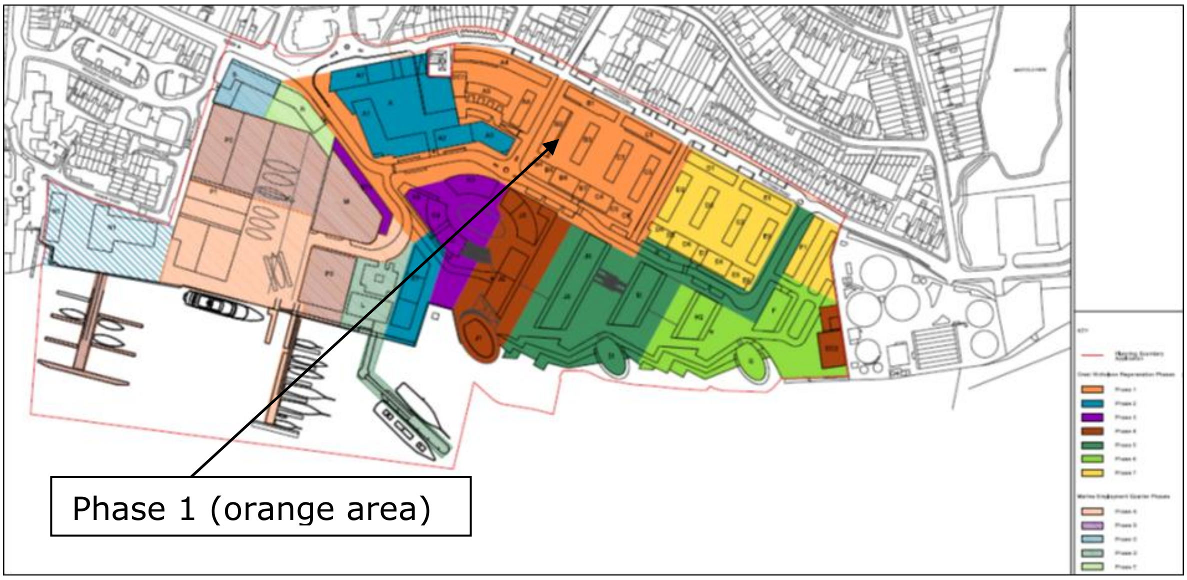


Figure 2 - Phases of Centenary Quay development showing Phase 1 area

2 About the building: design and construction audit, drawings and SAP calculation review

Technology Strategy Board guidance on section requirements:	This section should cover the project up until before commissioning. Give more details on the building type, form, materials, surrounding environment and orientation, as well as related dwellings in the development (which may or may not be part of the BPE project). Other amenities, such as transport links, cycling facilities, etc. should also be outlined where relevant to the design specification. Also provide comments on the design intent, construction process and the product delivered (including references to drawings, specifications, commissioning records, log book and building user guide). If the original specification is available, describe how closely the final design meets it, what the discrepancies are and why these occurred. Indicate whether the explanation comes from the design team or from evaluator judgement. Identify any discrepancies between the design and SAP and whether the design accurately reflected in the SAP calculations and describe where these discrepancies lie. Does the SAP performance match the specified performance and was this informed through measured or calculated data. As far as possible provide an explanation of the rationale behind the design and any changes that occurred. In particular, it will be helpful to understand the basis for making key decisions on the choice of measures and technologies. These may have been chosen to suit the particular property or a physical situation, or they may have been chosen to test an innovative material or a new product. List and describe any aspects of the design that are likely to introduce performance issues – e.g. cold bridges? Describe any aspects of the design that were a challenge to construct robustly - e.g. introduction of air leakage paths. Finally this section should also outline the construction and construction management processes adopted, construction phase influences i.e. builder went out of business, form of contract issues i.e. novation of design team, programme issues etc. Describe the overall construction process, highlighting any supply chain issues, delays in construction, contract(or) issues Important: please describe steps taken to overcome any stated challenges and issues. Report perceptions, concerns and positive nuggets raised by the client, designers, and construction team. Complete this section with conclusions and recommendations.

2.1 Introduction

A complete review of building design, construction and as-built SAP calculations was presented in the final report for Phase 1 of the project.

An overview of the design objectives and the built form of the development's dwellings along with a summary of the major findings of Phase 1 are presented in this section.

A more detailed description of the three monitored dwellings and their respective households is also presented to give context to the monitoring data presented in Section 7.

2.2 Overview of the design objectives

The main sustainability objectives of the Centenary Quay development are outlined in the design, sustainability and planning statements as submitted to support the original planning submission for the development. The local sustainability policy context required that the development complied with the resource conservation aims given in the Southampton City Council local development framework and sustainable development checklist. These local policies laid out some general design objectives in terms of sustainability criteria such as the reuse of land and buildings, use of recycled materials, use of natural lighting, adaptability of buildings, waste minimisation, water efficiency, renewable energy and district heating. Perhaps the most important aspect of the design at Centenary Quay in terms of sustainability is the creation of a new development-wide community heating system to provide heating and hot water for both domestic and non-domestic buildings in the scheme. The district heating network will ultimately be provided with heat via two energy centres powered by natural gas fired Combined Heat and Power (CHP) plant. The district heating system will be operated and managed by an Energy Services Company (ESCO) who will be responsible for maintaining the system and charging residents and building owners for their use of heat.

The original requirement for the site was to achieve an 'excellent' rating under the Ecohomes standard with an expectation that later phases would meet Code for Sustainable Homes level 3 or 4. The design objectives adopted by Crest Nicholson for the building fabric and systems in terms of their energy efficiency and carbon emissions are given in the Centenary Quay Sustainability Statement prepared by Fulcrum Consulting (2010 version). The design parameters were intended to exceed the requirements of the version of Part L Building Regulations in force at the time (Part L1a 2006 applies to Phase 1 of the development) and to achieve at least an additional 10% reduction in both regulated and unregulated carbon emissions averaged across the whole site through the use of low and zero carbon technologies. The requirements included a stated maximum target for the Heat Loss Parameter (HLP) of 1.1 through improved elemental U-values and more stringent air-tightness standards. At this stage, the dwellings were intended to have a minimum of 75% dedicated low energy light fittings and A or A+ rated appliances. According to the Fulcrum Consulting Sustainability Statement, the expectation was that the combination of fabric and system measures together with the community CHP heating would result in a total reduction in regulated carbon emissions of around 19% with respect to the requirements of approved document ADL1a 2006. When the site was taken over by the HCA, Crest Nicholson worked with the HCA to agree that the first phase, as covered by this BPE project, would be designed and built to achieve Code for Sustainable Homes Level 3 – a voluntary building standard. The final energy strategy with enhanced building fabric coupled with the community CHP is expected to achieve a carbon reduction of around 44% over Part ADL1a 2006.

In terms of sustainable transport, the development will incorporate the provision of new pedestrian and cycle routes. Existing bus routes will be improved and there is a local train station for journeys into Southampton town centre. In terms of water management and water use, the dwellings will be provided with dual flush toilets, low flow taps/shower heads and low water use appliances, with a target potable water use of 105 litres per person per day. A hybrid strategy has been adopted for surface water drainage which combines conventional piped drainage with a Sustainable Urban Drainage (SUDS) system, permeable paving, green roofs and the use of water butts to collect water from roofs.

2.3 Built form

The houses and apartments in the first phase of the development at Centenary Quay were all of traditional cavity masonry construction with the external walls formed from an inner leaf of concrete blocks and the external walls in the main of brick, but with occasional rendered block or timber-clad block for architectural interest. The wall cavity was 135 mm wide, fully filled with blown graphite-coated polystyrene bead insulation (Springvale Platinum Ecobead) and with reduced cross section stainless steel wall ties connecting the inner and outer leaves. The walls were lined with plasterboard on adhesive dabs. The internal partition walls were formed from lightweight steel frame stud work with a plasterboard lining. The roofs were of traditional cold roof construction with trussed rafters and 400 mm mineral wool quilt cross-laid over the ceiling plasterboard. The ground floors were constructed of suspended beam-and-block concrete with 70 mm rigid phenolic board insulation above and a 65 mm concrete screed surface. The party wall construction was designed to comply with the requirements of the Robust Detail E-WM-17 comprising two leaves of medium density concrete block, finished with plasterboard on adhesive dabs, with a 100 mm cavity fully-filled with mineral wool insulation batts and with cavity barriers at the junction between external and party walls. The intermediate floors were constructed using engineered timber I-beams which were built into the masonry walls. The windows were double glazed timber framed units manufactured by NorDan with low-E coating, argon fill and warm-edge low conductivity glazing spacer bars.

2.4 Description of the monitored dwellings and households

The monitored dwellings are 3-bedroom, 3-storey mid-terraced houses with identical orientation. These houses form part of a terraced block from the first phase of the Centenary Quay project and were completed in 2012. They are identical apart from minor differences in the dimensions of openings, handedness of internal layout, the position of balconies and façade treatments. An elevation drawing of the three plots is shown in **Figure 3**. Layout plans for Plot 118, as a representative dwelling, are also shown in Figure 4. Bedrooms 1 and 2 are located on the second floor; Bedroom 3 and the living room are located on the first floor, while the open plan kitchen and dining area are located on the ground floor.

Figure 3 - Front elevation of Plot 120 (left), Plot 119 (middle) and Plot 118 (right)

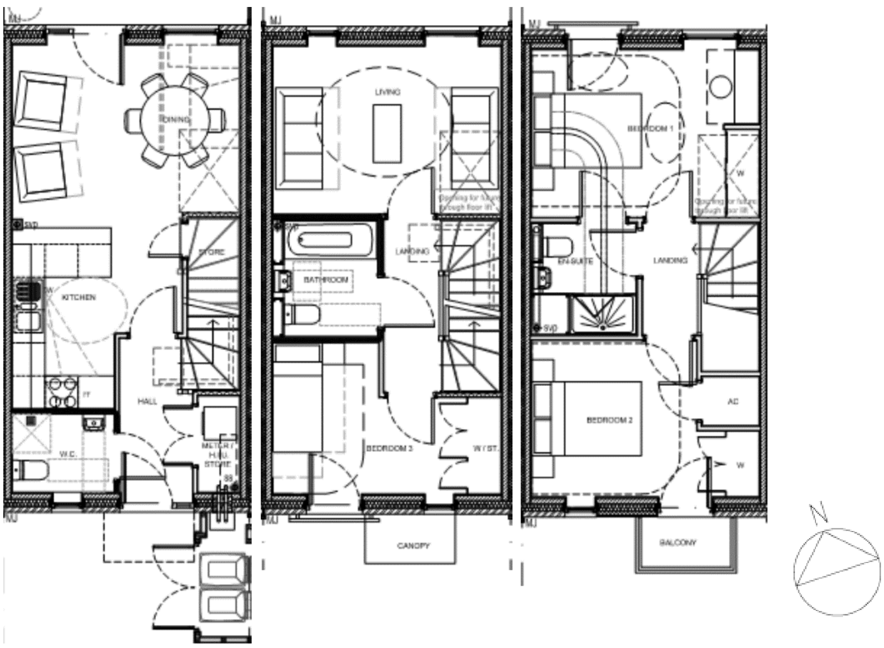


Figure 4 - Floor plans for Plot 118

The general dimensions, areas and volumes of the dwellings are listed in Table 1.

The main design input parameters used in the SAP calculation are given in Table 2. Any discrepancy between UCL findings in Phase 1 of this project and as-built SAP calculations are also highlighted in Table 2 to give context to the monitoring data that will be subsequently presented in this report.

Table 1 - Monitored dwellings' dimensions

Dwelling	Total Floor Area (m^2)	Internal Volume (m^3)	Average Room Height (m)	Ground Floor Area (m^2)	Roof Area (m^2)	Glazed Area (m^2)	External Wall Area (m^2)	Total Exposed Area (m^2)
Plot 118	103.32	271.39	2.63	34.44	34.44	14.72	44.74	135.63
Plot 119	103.32	271.39	2.63	34.44	34.44	13.17	46.29	135.63
Plot 120	103.32	271.39	2.63	34.44	34.44	13.14	46.32	135.63

Table 2 - Main input parameters in as-built SAP

Parameter	As-built SAP	UCL Review
Total floor area	103.3 m^2	103.3 m^2
Living room area	12.6 m^2 (first floor living room)	**25.0 m^2 (largest open floor area: kitchen/dining area)**
Ground floor U-value	0.15 W/m²°K	**0.17 W/m²°K (calculated)**
External wall U-value	0.21 W/m²°K	0.20 to 0.21 W/m²°K (calculated)
Roof U-value	0.11 W/m²°K	0.11 W/m²°K (calculated)
Window U-value	1.30 W/m²°K	**1.22 W/m²°K (manufacturer's specification)**
Opaque door U-value	1.60 W/m²°K	1.60 W/m²°K (Crest Nicholson general specification)
Air permeability	6.0 m³/h.m² @ 50 Pa	**7.34 m³/h.m² ± 0.27 @ 50 Pa (UCL pressure test result for Plot 120)**
Ventilation	MEV system with Appendix Q SFP data for Vent-Axia MVDC-MS: 0.21 W/l/s	**0.17 W/l/s (manufacturer's specification)**
Thermal bridging	Default y = 0.15 W/m²°K (SAP default value)	**y = 0.10 W/m²°K (based on calculation done for Plot 120)**
Thermal mass parameter	10.75 kJ/m²°K	10.75 kJ/m²°K
Heating	Community CHP with heating fraction 0.65 at 88% efficiency	**ENER-G E100 CHP unit with heating faction 0.59 at 81% efficiency (quoted by the manufacturer; for operational values see UCL review included in this section)**
Heating controls	Programmer, room thermostat, with TRVs	Programmer, room thermostat, with TRVs

Table 3 includes the heat loss coefficients derived from as-built SAP 2005 calculations for the monitored dwellings. It should be noted that the air permeability for Plot 120 measured by the UCL team was 22% higher than the value used in as-built SAP calculation. Furthermore, as reported in Phase 1, the in-situ U-value measurements carried out on Plot 120 revealed that actual U-value of the external wall was 0.34 W/m²°K, which is 62% higher than the value used in SAP calculations. Therefore, the heat loss coefficients derived from SAP are optimistic, and it is expected that actual heat loss coefficients would be higher than the values listed in Table 3.

Table 3 - Predicted heat loss coefficients based on as-built SAP calculations

Dwelling	Fabric Heat Loss Coefficient (W/°K)	Ventilation Heat Loss Coefficient (W/°K)	Total Heat Loss Coefficient (W/°K)
Plot 118	66.99	45.23	112.22
Plot 119	65.40	45.23	110.63
Plot 120	65.37	45.23	110.60

Table 4 includes the SAP target emissions rate and the as-built dwellings emissions rates for the monitored dwellings.

Table 4 - As-built dwelling emissions rate (SAP 2005 assessment)

Dwelling	SAP 2005 Target Emissions Rate (TER), kg $CO_2/m^2.a$	Dwelling's Emissions Rate (DER), kg $CO_2/m^2.a$
Plot 118	18.64	10.71
Plot 119	18.64	10.76
Plot 120	18.64	10.76

It should be noted that the Building Regulations compliance calculations are carried out under standardised operating conditions and, therefore, neutralise the effect of occupants' behaviour. In reality, energy performance of buildings could, to a large extent, be related to occupancy patterns and occupants' behaviour. Table 5 provides some information about occupancy in the monitored dwellings that could give context to the monitoring results presented in this report. For further information about occupancy pattern and occupants behaviour please refer to section 5 of this report.

Table 5 - Details and demographics of monitored households

Dwelling	Normal no. of residents	Tenure	Employed Yes/No	Gender of residents	Typical Occupation Pattern
Plot 118	2	Owner-occupier	Yes (both residents)	1 female, 1 male	At work during week
Plot 119	3	Rented	Yes (all residents)	1 female, 2 males	At work during week
Plot 120	2	Owner-occupier	One resident fully employed; one resident works part-time	1 female, 1 male	At work during week, except part time worker

2.5 Major findings of the project in Phase 1: Post-construction & early occupation

Major findings of the project in Phase 1 related to design, construction and the Building Regulations compliance calculations (as-built SAP) were as follows:

- Maximum U-values in construction specification were compared against the as-built U-values calculated by the UCL team. Details are included in Table 6**.** All as-built U-values were better than the maximum values except the ground floor U-value. This was partially due to a change in supplier, which resulted in a reduction in floor beam depth and the type of insulation used.

Table 6 - Limiting U-values as specified (Crest Nicholson General Specification/Building Regulation Notes Rev CA) and design U-values as calculated by UCL from drawing details (Crest Nicholson drawings 1042-H-400, 1042-H-423, 1042-H-120, NorDan Schedule of Quantities NO.0298479.Y)

Element	Maximum U-value in construction specification[W/m^2K]	As-built U-value calculated by UCL [W/m^2K]
External walls	0.23	0.20-0.23
Roof (pitched)	0.15	0.11
Ground floor	0.15	0.17
Windows and doors	1.6	1.22

- The construction specification makes no reference to the use of Accredited Construction Details (ACDs). Accredited Construction Details checklists have not been completed and therefore the y-value used in the SAP worksheet is the default backstop of 0.15 W/m^2K. However, most of the details would comply with the requirements of Accredited Details, which would give a significantly improved y-value of 0.08 W/m^2K. Crest Nicholson traditionally have a more rigorous approach to thermal bridging for buildings designed to meet their standard specifications, and would normally use the details from the Aircrete Products Association Constructive Details catalogue, which would give a further improvement in design y-value of 0.04 W/m^2K compared to the 0.15 W/m^2K default value used at Centenary Quay. Either approach represents an opportunity in future phases of the development to improve the designed thermal performance of the building fabric and/or to reduce build costs by offsetting improved thermal bridging heat loss with slightly worse heat loss in one of the other building elements.

- The construction specification contained no specific reference to an air permeability target. The as-built SAP worksheets have a designed air permeability of $6m3/h.m^2$ @50Pa. The 6 $m3/h.m^2$ target was based on previous test data collected from other Crest Nicholson developments and is in the Group Construction Specification. The result of the regulatory pressure test carried out on Plot 120 after completion of the dwelling was 4.94 $m^3/h.m^2$. There was a discrepancy between the envelope area in the test certificate and the area calculated by the UCL team. The regulatory pressure test result for Plot 120 after area correction would be 4.66 $m^3/h.m^2$.

- The heating energy to the monitored dwellings is provided by a district heating system and CHP plant via the Heat Interface Units (HIU) installed in the dwellings. As per the requirement of the Heating Compliance Guide 2006, good practice would have been to fully insulate the primary flow and return pipework on the district heating network that feeds the HIU. The primary pipework was insulated but there were gaps at the back of the pipe and the pipe supports. The valves and pipe connections were un-insulated due to the smallness of the gap between the wall and pipework which gap was determined by the dimensions of pipe clips used.

- Ventilation at Centenary Quay is provided utilising a centralised continuous Mechanical Extract Ventilation (MEV) system. Air is extracted via an MEV fan unit located in the loft through ceiling mounted air valves in the wet rooms (kitchen, toilet, & two bathrooms). The kitchens are fitted with a filtered re-circulating cooker hood above the hob. Fresh air is also provided by closable trickle vents integrated into the NorDan window frames. One of the findings of the construction review process was that there was extensive use of flexi-duct in the loft, especially at the connections to the fan unit. Whilst it is normal to use a small amount of flexible duct to make connections, the amount observed was excessive and had been laid in such a way as to form tight bends which would cause back pressure on the system and reduce the system performance compared to design assumptions. An examination of the flexible connections between the rigid duct and the ceiling vents showed that in many cases the flexible duct was constricted and not properly aligned (Figure 5), which would increase back pressure and reduce system efficiency.

Figure 5 - Extract terminals with diffusers removed showing constrictions in flexible ducting

It was also noted that the MEV boost mode in WC and bathrooms, which was triggered by the lights switch, did not have an over-run function, and the system would revert back to trickle mode when the light switch is turned off. A humidistat would ensure that boost mode operated for a long enough period after the bathroom was vacated and the light turned off to clear moisture e.g. from a shower.

- All of the fixed light fittings in the dwellings were of a proprietary type dedicated to low energy bulbs (as was required by 2006 Building Regulations) and as such would therefore meet the development target of a of minimum 75% low energy fittings. Residents would need to replace bulbs with ones of the same specification from TP24 and would not, for example, be able to use standard GU10 CFL or LED bulbs. Most light fittings were downlighters, and it was noted that some rooms had a relatively large number in comparison to the room floor area. For example, the living room had nine downlighters controlled by one light switch, which equates to 90W power consumption for the room. Such relatively high total power consumption would offset some of the benefits of using low energy bulbs.

- A Table including major SAP input data used in the as-built SAP calculations and the results of the UCL review of these input data is presented in Section 7 to give context to the monitoring data.

It is notable that, whilst being designed under the requirements of Part L1a 2006 in force at the time, the dwellings as designed would probably also meet the carbon emission targets in Part L1a 2010 due to the enhanced building fabric and the integration of the communal CHP system. So, for example, for Plot 120 the Part L 2006 TER is 18.6 kg CO_2/m^2.a with a DER from SAP2005 of 10.7 kg CO_2/m^2.a. The Part L 2010 TER for Plot 120 is 15.1 kg CO_2/m^2.a with the DER of 10.5 kg CO_2/m^2.a, still comfortably below the target emissions, albeit for Part L 2010 it is required to use SAP2009 to determine DER and TER.

2.6 Conclusions and key findings for this section

The design fabric performance of the dwellings at Centenary Quay was affected in various ways by errors or uncertainties in the calculation of elemental U-values. There was no detailed consideration of thermal bridging, with the SAP calculations using the very conservative default y-value. At this level of dwelling fabric energy efficiency, thermal bridging can account for a large proportion of fabric heat loss and therefore through correct application of the y-value, elemental U-values could be relaxed.

However, the impact of fabric performance at Centenary Quay in terms of designed carbon emissions is relatively low due to the overriding influence of the low carbon communal CHP system on emissions.

In terms of air-tightness, there was a nominal air permeability target of $6m^3/h.m^2$, although this was not stated in the construction specification or drawings. The air permeability performance was achieved through the installation of plasterboard and continuous dabs and, in addition, through the experience of the construction team and quality control measures.

Observations of the mechanical ventilation system as-built indicated that there were likely to be issues with performance due to flow restrictions, excessive use of flexible duct and insufficient door undercuts. See section 7 for operational performance.

A number of input errors were found in the SAP calculation, which would have affected the calculated Dwelling Emission Rate, but none of these were large enough to have caused the SAP assessment to fail had they been corrected.

There were some observed differences between the design specifications of some materials and those actually used on site. For example, a medium density block was specified for the inner leaf of the external wall, but an autoclaved aerated block was actually used in the construction. Although this change would have led to a better wall U-value, the change was not properly documented.

Designs that use cantilevered balconies that project through the insulation layer of the external wall are likely to cause problems both in terms of air-tightness and thermal performance. It is therefore recommended, as an alternative, that the project team consider the use of balcony designs that do not penetrate the insulation layer. For example, self-supporting balconies are commonly used in Passivhaus designs as these remain outside the thermal envelope.

3 Fabric testing (methodology approach)

Technology Strategy Board guidance on section requirements:	This section should provide a summary of the fabric testing undertaken as part of the mandatory elements of the BPE programme, *plus* any other discretionary elements that have been undertaken. Ensure that information on u-value measurements; thermography, air-tightness, any testing on party wall bypasses and any co-heating tests are covered. Give an overview of the testing process including conditions for the test any deviations in testing methodology and any measures taken to address deficiencies. Confirm whether any deviations highlighted have been rectified. As some tests (particularly the thermographic survey) are essentially qualitative it is important that the interpretation is informed by knowledge of the construction of the elements being looked at. Comment on the use of particular materials or approaches or their combination or installation methods lessons learned. Complete this section with conclusions and recommendations for future projects.

3.1 Fabric testing

The Final report for Phase 1 includes details of fabric tests carried out, including thermography of Plots 119, 120 and 121 and the results of co-heating test, in-situ U-value measurements and pressure tests for Plot 121 (end-terrace).

Of the three dwellings that have been subject to long term monitoring in Phase 2 of the project, Plot 120 was subject to in-situ U-value measurements and an air-pressure test.

The following Tables include the results of the fabric tests carried out on Plot 120 in Phase 1.

Table 7 - In-situ U-values of external elements: Plot 120

Tested element and location of heat flux sensor	Calculated U-value (W/m^2K)	Measured U-value (W/m^2K)
Plot 120 centre of external wall	0.20	0.37 ± 0.03
Plot 120 centre of external wall	0.20	0.34 ± 0.03
Plot 120 external wall adjacent to window	0.20	0.53 ± 0.03
Plot 120 edge of ceiling at junction with wall	0.11	2.59 ± 0.34

Table 8 - UCL air-pressure test results: Plot 120

		Air Permeability $m^3/h.m^2$ @ 50Pa		
Date	**Plot**	**Depressurisation**	**Pressurisation**	**Mean**
11/01/2013	120	7.54	-	-
11/02/2013	120	7.51	-	-
14/03/2013	120	6.95	7.55	7.25
28/03/2013	120	7.35	8.21	7.78
Mean and St. Dev.	120	7.34 ± 0.27		

3.2 Conclusions and key findings for this section

The external wall of Plot 120 appeared to be properly insulated at the location of the flux sensors used for the in-situ U-value measurements. However, the in-situ U-value measurements of the external wall in this dwelling showed that the measured U-value (0.34-0.37 W/m^2K) fell short of that calculated from the dimensions of the wall and the fundamental thermal properties of the components (0.20 W/m^2K). This result raises some concerns about the in-situ performance of elements compared to calculated values, and may be a result of factors such as tolerances, quality of installation, wind effects and convective air flow through insulation that may not be accounted for in-theoretical calculations of U-value or laboratory hot box testing.

The value of air permeability measured by UCL (7.34 $m^3/h.m^2$) for Plot 120 was around 57% higher than the regulatory test carried out on the same dwelling. The reasons for the discrepancy between the two sets of measurements are not known, but may be a result of the rapid failure of sealing measures carried out by the site team. The second test by independent experts commissioned by Crest Nicholson confirmed this may have been the case.

4 Key findings from the design and delivery team walkthrough

Technology Strategy Board guidance on section requirements:	This section should highlight the BPE team's initial studies into possible causes and effects, which may require further study. The section should reveal the main findings learnt from the walkthrough with the design and delivery team covering the early stage BPE process and the design intentions. Comment on lessons learned, key findings, conclusions and recommendations on what would be done differently next time. A critical feature of this section is reviewing the original aspirations for the project as stated by the design team and comparing with the delivered building. This often goes beyond what is stated in supporting documentation and is a crucial initial discussion which then frames the discussion about what changed during the process and why. The purpose of the walkthrough is to compare design intent with reality and why there is a gap between the two. Explore the degree to which the design intent has been followed through in terms of delivery and subsequent adoption by the occupant(s). Focus on what constraints or problems they had to accept or address in delivering the project. Cover construction team issues and how these were cascaded through the project for example: training for design team on utilising specific technologies and new materials, sequencing of trades. Describe and evaluate the documentation generated to confirm and record the commissioning and handover from specialist contractor to house builder. Include in the appendix if necessary. How did this process influence the design and delivery team walkthrough? Can anything be improved? Capture and assess how decisions were made and captured when the team are together e.g. the materials being used and whether they are required or desired – is there the possibility of changing materials and if so it this known by the procurement and constructions teams. Are there any issues relating to the dwelling's operation? This would include: programmers; timing systems and controls; lights; ventilation systems; temperature settings; motorised or manual openings / vents. Do the developer / manufacturer produced user manuals help or hinder the correct use of the dwelling? Have there been any issues relating to maintenance, reliability and reporting of breakdowns of systems within the dwelling? Do breakdowns affect building use and operation? Have issues been logged in a record book or similar? Add further explanatory information if necessary. Explain any other items not covered above that may be relevant to a building performance study. This walkthrough should be compared and contrasted with the occupant walkthrough (see later section) with comments on whether the design intent was desired, delivered and valued by the occupant and where and how differences between intent and expectation have arisen. If action was taken to remedy misunderstandings, improve support or feed occupant preferences into future design cycles this should be explained. Graphs, images and test results could be included in this section where

	it supports a developing view of how well or otherwise the design intent has been delivered during the pre and post completion phases. This section should provide a summary of the initial aftercare process, post completion building operation, and initial maintenance and management – particularly in relation to energy efficiency, reliability, metering strategy, building operation and the approach to maintenance i.e. proactive or reactive. Guidance on walkthroughs is available in the document *TSB BPE Domestic - Guidance on handover and walkthroughs.doc*, which can be downloaded from the Building Performance Evaluation site on `_connect'.

4.1 Overview of the project team review meeting

The assessment of the design and delivery process was carried out using a design team interview facilitated by the UCL research team in February 2013. A full account of this assessment was provided in the final report for Phase 1. The major findings that are of particular interest for Phase 2 of the project were as follows:

- A primary focus for Crest Nicholson was to reduce the overall carbon output from the new development. The initial energy strategy considered linking the site with the existing geothermal district heating system run by Southampton City Council; however, the cost of bringing the required district heating pipes across the Itchen Bridge was prohibitive. The decision was therefore taken to develop an independent district heating system for the development. Biomass-fired heating was initially considered, but there were concerns about the supply of sufficient biomass material. Given the size of the Centenary Quay scheme, a gas-fired CHP system was chosen as the more appropriate system. The original partner chosen to design and develop the CHP scheme was unable to find sufficient finance to bring the scheme to fruition. Crest Nicholson had to therefore turn to E.ON to complete delivery of the district heating system. Consequently, E.ON inherited a CHP scheme not originally designed by them, and had limited flexibility to change key aspects of the specification such as the pipe-work, HIU units and main plant.

- This was the first time the project team had delivered a CHP district heating system at this scale, which naturally led to some uncertainties in design decisions. Crest Nicholson has stated that proposed regulatory changes, uncertainty about how political factors might influence planning and regulation, and the lack of appropriate tools and technical support made the design process even more challenging.

- The selection of MEV for the ventilation system over a Mechanical Ventilation with Heat Recovery (MVHR) at Centenary Quay was made on the basis of cost, efficacy and efficiency. Another stated reason was to concentrate on maximising efficiency from the district heating network and not to have heat recovery distributed around the site. Furthermore, the building services engineering consultancy had experience with poor installation practice and badly commissioned MVHR systems on other sites, and was not confident in the capability of the supply chain. So, whilst MVHR had been considered in the early stages of design, concerns about installation issues, cost and perceived likelihood of negative customer reaction meant that it was not taken forward to the final design. Crest Nicholson now have a company-wide policy (which was not in effect at the time the scheme was designed) that requires the use of Mechanical Ventilation with Heat Recovery (MVHR) systems be justified due to concerns about their effectiveness.

- The installation and commissioning of the MEV system was discussed. It was noted by the participants that Phase 1 of Centenary Quay comes under Part F 2006, and therefore the approved documents do not require the system to have a commissioning certificate. Phase 2 is being built under the requirements of Part F 2010 and will therefore need to be commissioned in line with the Domestic Ventilation Compliance Guide 2010. It was recognised by the project team that they have had issues with the performance of ventilation systems in the past and that, where systems don't work as designed, there is potential for mould and health issues in the dwellings where the air leakage value is very low.

- The project team reported on some of their experience with the final handover of the dwellings to the residents and feedback from customers with regard to the performance of the dwellings. It was felt that the handover conducted with private sale customers resulted in the customers' better understanding of the operation of the heating and hot water system when compared to the Housing Association tenants.

- Various concerns were expressed about the way that different residents' use of their houses might affect the performance of the dwellings. These included taping over trickle vents due to draughts, and condensation problems caused by drying clothes indoors. In the first few months, the sales teams reported that there had been numerous complaints about the heating system, mostly about reliability, leaks or the relatively slow response times of the heating system in cold weather. It was reported that some residents were struggling to programme the heating controllers or to set the TRVs. In response to this feedback, both Crest Nicholson and E.ON have delivered a series of open days to help residents better understand how to optimise their heating and this programme continues.

4.2 Conclusions and key findings for this section

Some of the key lessons from the Centenary Quay project have been around the difficulties with the procurement, installation and commissioning of the district heating system. Certain factors were outside the control of the project team, such as the need to change the ESCO delivery partner for the district heating system. With the benefit of hindsight, perhaps more could have been done at the start of the project to understand the technical implications of the system and trade-offs with fabric performance. Some of these lessons have already been fed back into the second phase of the development, such as making the district heating contractor responsible for installation, commissioning and management of the system.

Despite the issues with the heating system and HIUs, it has nonetheless been demonstrated that it is possible for the project team and subcontractors to work together to deliver a complex district heating system under difficult circumstances.

The design of the development was perhaps overly complex, and this led to difficulties in optimising cost and performance of the dwellings. Some problems will have been caused by changes necessitated by the economic situation, but design and construction processes need to be robust enough to cope with such changes, albeit in this case the downturn was rapid and severe and caused loss of valuable experience from project teams. Despite this, the CQ project team and subcontractors have overcome these problems and delivered a scheme with character, which the majority of residents are very happy with.

One key recommendation is for the project team to improve their change control processes, which would enable them to better cope with issues such as unforeseen changes to the design or problems with contractors.

Crest Nicholson has a detailed Change Request procedure in place to manage necessary changes to a scheme after detailed Planning Permission has been submitted to a local council. This includes for changes to the construction or internal specification, construction details, the site layout or dwelling types. The procedure makes individuals responsible for the changes they request and ensures that the senior management team understand the implications of the change and are accountable for their decision. In part due to the recommendations from Phase 1 of this project, Crest Nicholson has reinforced the importance and mandatory nature of the procedure across the business.

The issue of ventilation strategy and problems with the installation and commissioning of mechanical ventilation systems has been a challenge for the project team. The approach to ventilation is closely linked with the strategy for air-tightness, and it is apparent that these issues were not fully resolved in the design development of the first phase. These problems are clearly demonstrated by the test data which show that the performance of the MEV systems as installed is unlikely to meet regulatory requirements and that there have been significant changes in air-tightness test results over a short period of time (for further information about the performance of the installed MEV systems please refer to section 7.8). It is recommended that the project team work with its consultants to develop a strategy for both ventilation and air-tightness, taking into consideration the requirements of both existing regulations and proposed changes.

The results from the Phase 1 performance test and Phase 2 monitoring data have helped Crest Nicholson to recognise the design and installation challenges that continuous MEV systems involve, mainly concentrated in the ducting arrangements. Crest Nicholson still consider an MEV system to be the best solution for air quality, user friendliness and cost. However, a decision has been made to move to decentralised MEV systems where duct lengths are minimised to offset the issues outlined above. In addition, Crest Nicholson has updated its workmanship specification to insist that all installers are BPEC qualified.

Another recommendation is to improve the handover between the design and construction processes. There needs to be better communication between the design and construction teams and, in particular, improvements to the way that design and technical information is transferred.

In its standard set of procedures, Crest Nicholson requires the use of Project Vault, a database that provides clear structure and rigid procedures for drawing production. The standard set of procedures also requires a meeting between the Technical and Build teams to ensure a smooth transition and handover. The meeting follows a standard agenda and covers all aspect of the project, including its history, work-to-date, drawings package, build-ability, etc. When the project is complex, key external consultants are included. At the end of this handover meeting, the commercial and build team will have a complete picture of the project to enable them to ensure an accurate scope of works is developed for all trades and can be effectively managed during construction. Due to certain circumstances, this handover meeting did not take place for the first phase at Centenary Quay but has taken place for subsequent phases and will happen in the future.

Training of site operatives also needs to be improved to minimise the occurrence of ad-hoc design, so that dwellings are built as designed. Better feedback mechanisms between the construction and design teams would help inform future designs, with the potential to improve build-ability and reduce the risk of underperformance.

The complexity of the design was also an issue. It is therefore suggested that there needs to be more design effort up front that seeks to improve build-ability and reduce complexity, whilst at the same time maintaining the aesthetic and architectural interest of the dwellings.

There were clearly issues for the project team in terms of the pace of change with respect to Building Regulations (England and Wales) and energy performance targets. This is a particular problem for large developments such as Centenary Quay, where the design and construction process can span over a period of several regulatory changes. Developers such as Crest Nicholson require certainty about proposed changes well in advance of implementation so that they can manage the process of change cost-effectively and adapt to the technical challenges necessitated by the journey towards zero carbon homes.

The Centenary Quay project was delivered by Crest Nicholson Regeneration (CNR) who until recently operated on a main contractor model, now adopting a direct build approach. The first phase at Centenary Quay, on which this research is based, was the first development CNR have delivered under the direct build approach. This change of procurement method is significant, and demands different skill-sets and new ways of working. Some of the issues highlighted by the research will result from this transition and the need to establish and embed new processes both internally and with external consultants and subcontract teams.

5 Occupant surveys using standardised housing questionnaire (BUS) and other occupant evaluation

Technology Strategy Board guidance on section requirements:	This section should reveal the main findings learnt from the early stage BPE process and in particular from the Building Use Survey. This section should be cross-referenced with findings from the occupant handover process and be informed by the design and delivery team walkthroughs. This section should draw on the BPE team's initial studies into possible causes and effects, which may require further study. BUS information will be stored in the data repository, but the link for BUS anonymised results should be included in this report. The BUS results come in 3 forms: • An anonymous web-link that will contain the result and benchmark graphic for each variable (question), a summary of the 12 main variables and some calculated summary variables. • Appendix A (.pdf) which contains largely the same set of results and graphics as the link above. • Appendix B (.pdf) which contains all the text comments from the questionnaires Reference the variable percentile scores, which show the percentile that the score is ranked at in the benchmark set, and comment on as appropriate. **Important:** The comments from Appendix B can be used in this section. However, great care must be taken when using comments to ensure that no personal information is divulged, no individual can be identified and no confidentiality is breached when publishing the comments. This is especially important if referring to a respondents' background. Graphs, images and test results could be included in this section where it supports a developing view of how well or otherwise the design intent has been delivered during the pre and post completion phases. Note where the dwelling is being used as intended and where it is not; what they like / dislike about the home; what is easy or awkward; what they worry about. It should cover which aspects provide occupant satisfaction and which do not meet their needs, result in frustration and / or compensating behaviour on the part of occupants. Any misunderstandings occupants have about the operation of their home should also be addressed. Are there any issues relating to the dwelling's operation? This would include: programmers; timing systems and controls; lights; ventilation systems; temperature settings; motorised or manual openings / vents. Do the developer / manufacturer produced user manuals help or hinder the correct use of the dwelling? Have there been any issues relating to maintenance, reliability and breakdowns of systems within the dwelling? Do breakdowns affect building use and operation? Does the occupant have easy access to a help service? Does the occupant log issues in a record book or similar? Does the occupant have any particular issues with lighting within the dwelling (both artificial lighting and natural day lighting)? Add further explanatory information if necessary From the occupiers point of view what improvements could be made to the dwelling to make it more user friendly and confortable to live in. Cover what the teams' would do differently in future (or wanted to do differently but could not) and why.

5.1 BUS survey and initial interview with the occupants

The BPE domestic BUS survey was distributed to 76 apartments and 92 houses located in the Phase 1 of Centenary Quay development in December 2012. A total of 24 responses were received back by the deadline, giving a response rate of 14%, although not all the responses were complete. 15 respondents live in houses and 9 respondents live in apartments. An overview of the BUS results was provided in the final report for Phase 1. The web link for the anonymised BUS data for Centenary Quay is: http://www.busmethodology.org/9051/

An initial interview with the residents was also carried out and reported in the final report for Phase 1.

5.2 Second interview with the occupants

Three second-round occupant interviews with the residents in Plots 118, 119, and 120 were carried out on 19/20 March 2014. These complement the interviews that were carried out and reported in Phase 1.

5.2.1 Property type

Occupants of Plots 118 & 120 are owner-occupiers, and those of Plot 119 are tenants. The interview with Plot 119 took place in the early evening of 19 March 2014. Plots 118 & 120 were both interviewed on the evening of 20 March 2014. All three houses are three-bedroom terraced houses, in a terrace of four houses. The houses are adjacent to each other. They are on three-stories and are of brick-block cavity wall construction. There is no garage; one on-street parking space per house is provided at the front. There is a small front and a medium sized back garden. At the end of the back garden is a shed with room for storage of garden equipment and bicycles. The configuration of the interior of the house is unusual with the kitchen and dining room located on the ground floor, the living room on the first floor together with a second bedroom and a small bathroom. The master bedroom with an en-suite bathroom is on the top floor. At the time of the second- round interviews, all occupants had been in their houses for more than 12 months.

5.2.2 Occupants' profiles and lifestyle

The occupants in Plot 118 are a couple, both young professionals aged between 20 and 40. They are non-smokers and are in full-time employment. Both work regular office hours and had not been away for holidays at the point of interview. The occupants reported that they had purchased additional electrical appliances such as a dishwasher, a vacuum cleaner and a

Smart TV since the first interview. The house seemed to be more furnished than 12 months ago.

While the occupants said in the last interview that they used the open plan lounge/kitchen most of the time, this time they reported that they were spending considerably more time in the Living room watching TV.

Residents in Plot 119 are a married couple and their male relative (a brother). They had moved to Centenary Quay from Birmingham. Both the male occupants continued to work full-time. The female occupant appeared to have found employment since the first interview. This means that the house is less occupied than when they first moved in around April 2013. They reported that they tended to leave the house at around 8.15 am and to return at about 6.00 pm. At the time of the second interview, they had been in the house for a full year.

Occupants of Plot 120 are a married couple who moved to the development with the aim of starting a family. They have a moderate income as only the female occupant has a full time job. However, since February 2014, the male occupant has been in part-time employment. He said that he would typically go out at 7.00 am and be back around 3.00 pm. This would mean that like both Plots 118 & 119, Plot 120 would mostly be unoccupied during the day. The couple are in their 30’s, and are non-smokers.

5.2.3 Likes and dislikes about the property

Occupants in Plot 118 said that they still liked the house as it was spacious and had a bathroom on each floor. It has a sea-view and was close to the railway station (convenient for commuting to work). Dislikes included the fact that their backyard was constantly in the shade. They said that it would be nice to have [some] sun, and that guest parking was a constant issue that had become more noticeable as time went on.

While Occupants of Plot 119 enjoyed the spaciousness the property offered, they appeared to have become more dissatisfied with the interior condition of the house as time had passed, noticing “edges of carpet coming up or cracks…more than what is normal”. They were also disturbed by the noise from the ships at night and the noise generated by children playing around the neighbourhood: "we have got loud neighbours with crazy kids, people fighting. There is just a lot more here than there [previous accommodation]."

Occupants in Plot 120 felt the area on the whole was quiet but there was noise from the neighbourhood - "we had children jumping [around]. It was noisy". They would have liked the configuration of the kitchen/dining to have been reversed i.e. with the kitchen at the back of the house rather than the front, so that they could open the window while they were cooking. They complained about draughts in the front bedroom on the 2nd floor.

5.2.4 Awareness of energy saving features and thermal comfort

Occupants of Plot 118 seemed to have become more positively aware of the energy saving features of the development. For example, the occupants reported that they noticed the energy efficiency of the windows and their effect on how long the house would stay warm. They remarked:

"When you turn the heating off, the temperature goes down very slowly… if we do not have any windows open or any doors open."

They were delighted that the heating system was intelligent and controllable and that they could programme the heating according to their day-to-day needs. They reported that they would also use the TRVs (thermostatic radiator valves) to control the temperature of each room independently according to room use – with a setting of “3” for those rooms that they inhabited frequently (kitchen/dinning, lounge, and master bedroom), “1” or “1 and a half” for rooms that were used less frequently.

Occupants felt there were draughts coming through the trickle vents. These were particularly noticeable in winter. Therefore, they closed these vents in winter and they suggested that they would probably open them up again in summer.

When asked about how thermally comfortable they felt at the time of the interview, the male occupant said that he was very comfortable but the female occupant thought that it was ‘slightly cool’ indicating that her husband liked to have the house run cooler than she did [the internal temperature as indicated by the programmeable thermostat was 21°C at the time of interview]. She said she coped with the difference by wrapping ‘herself under a blanket’.

Occupants of Plot 118 felt that their bedroom could be quite warm in summer. Because there was neither a fan nor air-conditioning, they tended to open their windows.

A clear gender difference in perceived thermal comfort also emerged at Plot 119. Based on the 7 point Thermal Comfort (7 point ASHRAE) Scale, the female described the house as slightly cold while the males said that it was comfortable. She also felt that the house was generally warmer at weekends, according to her, because the house “heats up naturally”. During the week, they typically felt cold when they arrived home and the heating was not turned on, but it warmed up very quickly. They said that they had set the programme so that in summer, the heating would be turned off, as there was no need for it. And in the winter (around November), they would “put it to timing”. The occupants pointed out that the heating was turned off at the time of the interview [March]. In general, the occupants felt the heating system was controllable. However, they reported that they had been very cautious in turning on the heating system since they found the heating bill was ‘insanely’ high. One of them said - ‘If we are really cold we just turn the heating on but after looking at the heating bills we just put some extra clothes on because they are insane.’ However, the occupants said that some of the TRVs were on three or four (kitchen/dinning) while some of them were completely off. While they said that they had the heating off, they also reported having the heating on at up to 20°C (they labelled it as medium) at regular intervals throughout the night. They described how the system was working as follows:

“The only time when it is on overnight is between 11-12pm and then it turns on again at 1 am, 3 and 5am.”

This seemed to contradict occupants’ earlier description of their own heating behaviour and suggested that the system was not completely off as earlier implied. The lack of consistency in their comments might reflect the complex occupancy in Plot 119, in which the heating system was not necessarily controlled or managed by a single individual.

There were also some difficulties in handling cooling in summer because of differences in perceived thermal comfort between the males and the female occupants in this household. The male occupants (the husband and even more so, the brother-in-law) said that they would often open windows and doors in summer because they liked it cool. However, the female occupant would keep them closed because she easily felt the cold, and commented- “Unless it is really warm… In the evenings I do not open the window because it gets cold.’ Often, the female occupant would resort to using extra blankets to reconcile these differences.

It was observed that occupants of Plot 119 had paper blinds on all windows. Self-adhesive tapes used to hang these blinds had led to all trickle vents being blocked. The occupants were unaware of this. They reported that they had never opened any of these blinds as they felt enough natural light could still come through.

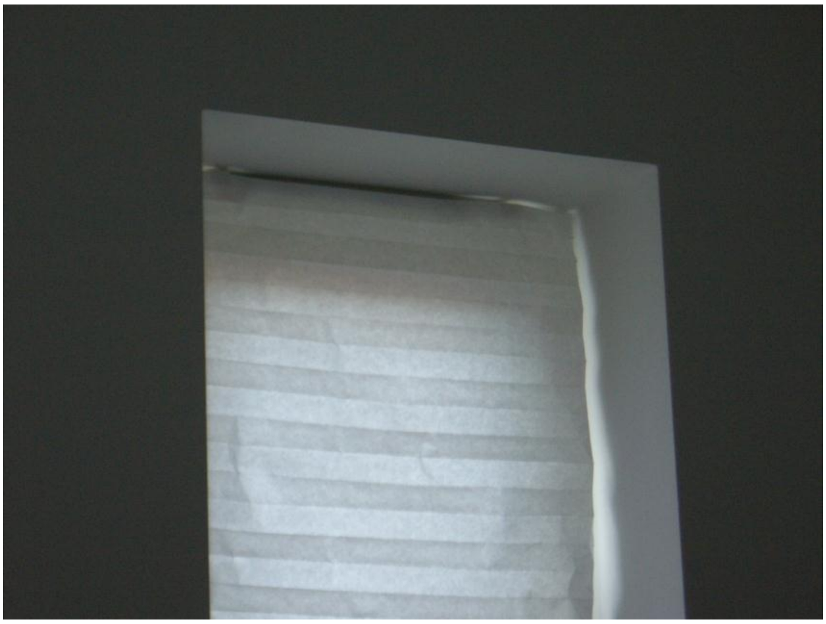


Figure 6 - Paper blind installed on the window led to the trickle vent being blocked

For Plot 120, they felt that on the whole the temperature was 'comfortable', and that design of the heating system was good as they could heat the house how they wanted. They remarked- "We use the heating if we want it to be warm". The female occupant said that they would normally put the heating up to 20 °C manually when they felt cold (the thermostat was set to 17 °C at the time of the interview). And they ran their house at an average temperature of 18 °C. The female occupant said that she would set the programmer as a week's programme to keep the temperature constant at 18 °C. They said they would change the temperature manually at weekends. She described their heating regime as:

"It is just set from Monday to Sunday – for every day. Let’s say I set it at 18°C in the morning. When I come back and I think the house is very cold I just press one-hour high temperature that does to 20°C just to warm it up. The heating would come on at 6.00 am and off at 10 pm. That would just stay for one hour and warm the house. Then it goes down back to 18°C."

She further elaborated that the heating was on constantly in winter, and kept to lowest temperature possible overnight. However, by spring (when the interview took place), she would not have the heating on at all.

Occupants reported that there were draughts in the two bedrooms on both 1st and 2nd floors on the front-side of the house. Consequently, these two bedrooms were very cold and they often wondered how young babies could inhabit these rooms. They remarked “When the winds are blowing you cannot sleep in these rooms”. And indeed, it was observed that there was a considerable air gap between the windowpane and the frame of one of these windows during the Walk Through.

When questioned about window opening behaviours, the female occupant said that the windows were kept shut for the majority of the time. The windows would only be opened in summer.

5.2.5 Walk Through

The occupants of all three households led the interviewers to each room in turn, beginning with the living room and the kitchen. In each room, the interviewer asked them about room use, thermal comfort based on a presentation of the Thermal Comfort Scale, noted the TRV setting, window opening behaviour, and broader comfort factors such as air quality and natural/artificial lighting.

There were no serious observable issues pertaining to odour due to damp or moisture in these houses. Occupants were, by and large, satisfied with the amount of both natural and artificial light provided.

Table 9 summarises occupants' reported room use, perceived thermal comfort and control of heating through the TRV in each room.

The Walk Through revealed the dynamics of complex behaviours in relation to the physical conditions of the houses, the interface of the heating and ventilation system and fabric, and the perceived cost of thermal comfort. The heating control behaviours of the occupants appeared to be strongly and primarily influenced by the perceived use and cost of heat. All three households complained about high heating bills.

If physiological and sex differences are discounted, occupants in Plot 118 reported having greater thermal comfort (heating system running at 21 °C at the point of interview) in comparison with Plot 119 and Plot 120, with occupants having a better sense of control of the heating system. All the rooms in Plot 118 are used more or less as the design intended. Occupants in Plot 118 reported that they had initially had a problem with their heating bills but this was sorted out with the provider E.ON. They are now fairly content.

It is very clear that Plot 120 suffers from a degree of heat loss through a gap in what appears to be a poorly fitted window in one of their bedrooms. In an effort to control their fuel bills, they economised by turning most of the TRVs off, running their house at lower temperature (recorded as 17.1 °C at the time of interview). Similar to Plot 118, all rooms of this house are used as the design intended.

The situation in Plot 119 is quite different from Plot 118 and Plot 120. The house is normally occupied by 3 adult occupants and a string of frequent visitors. It was observed that the living room on the first floor is permanently used as a guest room, and the ground floor dining area has a large sofa and is quite obviously used as a common living area for all of the occupants. The occupants' window opening behaviours appeared to be strongly influenced by physiological differences between male and female occupants. The frequent opening of windows for ventilation by some of the occupants and the effect of turning the TRVs off for economy will be important factors in the thermo-physical behaviour of the dwelling. In addition, occupants in Plot 119 reported that each person has at least 2 showers per day. Twice as many showers are taken in Plot 119 than in the other two houses. It is suggested that in considering occupants' heat consumption behaviour, aspects of culture and lifestyle related to hot water use may also need to be taken into consideration.

Table 9 - A summary of room usage (activities), perceived thermal comfort and observed TRV position

House No	**118**			**119**			**120**		
Rooms	Thermal Comfort Scale	TRV position	Activities	Thermal Comfort Scale	TRV position	Activities	Thermal Comfort Scale	TRV	Activities
Kitchen	Slightly warm	3		Comfortable/ Warm (weekends)	4/off		Comfortable	off	
Dining Room	Comfortable	3		Comfortable Slightly Cool	4/off (was off at time of interview)	Sitting room with Sofa	Comfortable	off	
Living Room 1/F	Comfortable/ Slightly cool	3		Warm	On/off	Guest Bedroom	Slightly cool	2/3	As and when
Bathroom 1/F	Slightly warm	3	Use to try towel	Comfortable	On/off when in use		Comfortable	off	
Front Bedroom 1/F	Cool	2	Use to ironing	Cool with draughts		Brother-in-law's bedroom	Cool/ Draughty	gap	Guest room
Master Bedroom 2/F	Slightly Warm	3.8		Comfortable/ Cool for the female	On/off	Lots of window opening	Cold	3.5	
En-suite Bathroom 2/F	Comfortable	3		Slightly cool	On/off		Comfortable	1-2	
Small Bedroom/ Study 2/F	Cold	1.9		Warm	Off	Use for ironing and drying	Cool	off	
Registered temperature on thermostat	21 °C			18.8 °C (with photographic evidence at time of interview)			17.1 °C		

5.2.6 The awareness of the HIU and district heating system

The occupants appeared to be aware of the HIU as part of the whole system that provides heat and hot water to their house. However, when asked what things use more electricity (note that text of the question referred to electricity and not to heat) in the house in a separate question, occupants of both Plot 118 and Plot 120 seemed to think that the 'heaters' or the 'hub' (referring to the radiators and the HIU) used most electricity. This appears to reflect a lack of understanding of the distinction between electricity and heat which exists despite the fact that they receive heating bills and electricity bills separately. One occupant said that they had never put on the booster in their kitchen because it might be 'expensive' as they believed that it consumed a lot of electricity. This is despite the fact that the actual amount of electricity that it consumes, even on boost mode, is small.

5.2.7 Overall satisfaction with the house

Despite the perceived high heating bills, all occupants were very satisfied with their property.

With respect to occupants' overall satisfaction with their property, a set of 20 questions covering preferences, control over thermal environment, other broader comfort factors such as air quality, noise, natural/artificial lighting, design and layout, as well as the costs of energy were asked. Occupants in Plots 118, 119, and 120 had overall satisfaction scores of 19/20, 10/20, and 16/20 respectively.

Of the 3 households, occupants in Plot 118 were most satisfied with their property, and seemed to have achieved greater thermal comfort. They have been happier with their energy bills since resolving some of the issues with the energy provider.

On the whole, occupants of Plot 120 felt very positive about their property (overall satisfaction score 16/20). They said that if they were able to change anything it would be to have direct access to the back garden from the street, without going through the house. The level of noise inside and outside the house was an issue for them, and they perceived their heating bills to be too high.

In contrast, Plot 119 was most dissatisfied of the three (overall satisfaction score of just 10/20). They felt they had less control over the temperature in their present home compared with their previous one. They were not satisfied with the level of noise inside and outside the home. The lack of separate access to the garden and parking space for guests remained an issue for these occupants. They were also most unhappy with the heating bills, which they perceived as 'expensive'. They suspected that they may have been billed incorrectly.

5.2.8 Desirability

All households felt that their friends and relatives who visited were pleased with the property and felt it was very desirable.

5.3 Conclusions and key findings for this section

Putting aside issues of perceived thermal comfort and heating bills, in general, the occupants were very satisfied with their property. They particularly like the space it provided and its design and layout. Two households would like to have access to their garden directly from the street, without going through the house and one household would like to have a kitchen at the back rather than at the front of the house.

All households used a type of paper blind mainly for privacy purposes. In Plots 119 & 120 these were taped to the top of the window frame, which meant that the trickle vents were blocked. In case of Plot 118, the trickle vents were shut throughout the winter because of draughts.

Assessment of energy consumption of the different households needs to take account of the different lifestyles and changing work patterns. The consumption of hot water is likely to have a significant influences overall heat consumption in these well insulated dwellings. It is likely that the number and relationships between occupants, habits of showering, and activities and use of rooms may significantly affect the consumption of heat.

It is important to note that all households had had problems with their heating bills when they first moved in. Occupants in Plot 118 reported that they had negotiated successfully with the energy provider and were now happy with the service. However, occupants in Plots 119 & 120 reported continued high heating bills, which they had attempted to control by turning the TRVs on their radiators down or off. Occupants typically opened their dining room window or door while they were cooking (particularly Plots 119 & 120) for fear that using the ventilation booster switch in the kitchen might be expensive. The combination of these behaviours appears likely to lead to an unstable internal temperature field, with significant variations over time and between different rooms. This in turn might have contributed to perceived thermal discomfort, while not necessarily achieving significant reductions in heating bills. The situation was most acutely felt in Plot 120, where interviewers observed that there was a badly fitted window in the small front-bedroom on the first floor. Occupants appeared not to be aware of how this could be remedied.

6 Installation and commissioning checks of services and systems, services performance checks and evaluation

Technology Strategy Board guidance on section requirements:	Provide a review of the building energy related systems, including renewables, regulated and unregulated energy and additional energy users that fall in to different areas (such as pumps for grey water use) and any results found. This section should enable the reader to understand the basic approach to conditioning spaces, ventilation strategies, basic explanation of control systems, lighting, metering, special systems etc. Avoid detailed explanations of systems and their precise routines etc., which will be captured elsewhere. The review of these systems is central to understanding why the building consumes energy, how often and when. Where possible this commentary should be split into the relevant system types. Explain what commissioning was carried out, what problems were discovered and how these were addressed. Discuss as to whether the initial installation and commissioning was found to be correct and any remedial actions taken. Prompt for any training scheme or qualifications that were found to be required as part of the study. Comment on whether the original operational strategy for lighting, heating/cooling, ventilation, and domestic hot water has been achieved. Compare original specification with equipment installed, referring to SAP calculations if appropriate. Give an explanation and rationale for the selection and sizing (specification) of system elements. Use this section to discuss the itemised list of services and equipment given in the associated Excel document titled *TSB BPE_characteristics data capture form_v6.xls*. For each system comment on the quality of the installation of the system and its relation to other building elements (e.g. installation of MVHR has necessitated removal of insulation in some areas of roof). Describe the commissioning process Describe any deviation from expected operational characteristics and whether the relevant guidance (Approved Documents, MCS etc.) was followed. Explanation of deviations to any expected process must be commented in this section. An explanation of remedial actions, if any, must also be given. Describe the operational settings for the systems and how these are set. Comment on lessons learned, conclusions and recommendations for future homes covering design/selection, commissioning and set up of systems. Also consider future maintenance, upgrade and repair – ease, skills required, etc. The document for capturing commissioning information is titled *TSB BPE_Domestic_commissioning sheets.doc*, which can be downloaded from `_connect'.

6.1 Mechanical ventilation system

As explained in the final report for Phase 1, the mechanical extract ventilation (MEV) systems at Centenary Quay were designed by the M&E sub-contract designer to be compliant with the requirements of Part F 2006. The designed trickle and flow rates for Plots 117 to 121 were provided on the M&E drawings and are given in Table 10. A check of the design extract flow rates for the individual rooms and for the total flow, and the expected targets as calculated by UCL show that the quoted flow rates would meet the requirements of Part F 2006 based on the number of wet rooms and the gross floor area, although the M&E designers have used slightly different floor areas than those calculated by UCL.

Table 10 - Design flow rates for MEV system given on drawings for plots 121-117 (inclusive of the monitored dwellings)

Room	Design trickle extract flow rate (l/s)	Design boost extract flow rate (l/s)
Kitchen	11.3	13.0
W/C ground floor	5.2	6.0
Bathroom 1st floor	7.0	8.0
Bathroom 2nd floor	7.0	8.0
TOTAL	30.4	35.0

The total air extract rate at the design trickle setting is just under 0.5 air changes per hour. No commissioning certificates or any other test data were provided by the project team for the test dwellings or indeed any other dwellings on the development. There is no requirement to provide mechanical ventilation system commissioning certificates under the Part F 2006, although they would have been required had the system been designed under Part F 2010. We were assured by the M&E sub-contract installer that flow measurements had been carried out and the MEV systems had been balanced in line with the design requirements, but that the flow readings had not been recorded. However, as the performance inputs to SAP 2005 for the specific Vent-Axia MEV system installed were taken from the SAP Appendix Q database, then there is a requirement to provide Appendix Q MEV commissioning checklists to both the SAP assessor and the building control officer. As far as we are aware, these commissioning checklists have not been submitted for any of the dwellings at Centenary Quay.

6.2 Heating and hot water system

The nominal flow temperature of the communal heat main is around 80°C and one would expect a temperature close to this, with some reduction related to the length of communal pipework between the dwelling and the energy centre. However, investigations in Plot 120 and its adjacent Plot 121 in Phase 1 of the project revealed that the district heating flow temperature recorded by the heat meter in the HIU was approximately 71°C in one plot and slightly higher at 77°C in the other plot. Given that the dwellings are next to each other, one would not have expected much difference in the flow temperature from the communal main. As district heating temperature is only controlled from the plant room, this would perhaps suggest either an error in one of the heat meter temperature sensors (for example if the sensor is not properly seated in the pocket), variability in the temperature of the communal flow, or mixing of the flow and return water via the system bypass located just below the HIU between the incoming communal flow and return, although this seems unlikely.

It was also noticed that the district heating supply was still periodically called for by the HIU even during periods of no space heating or domestic hot water demand. Further investigation revealed that this is a normal function of domestic hot water temperature control in this system with a “keep hot” type facility managed by a temperature sensor in the DHW heat exchanger which keeps the heat exchanger primed to reduce the lag time for hot water production. However, this will reduce the overall efficiency of the system and could increase the summer overheating risk. To a substantial extent, the keep hot facility duplicates the function of the bypass, which (as noted above) is also fitted just below the HIU.

6.3 Conclusions and key findings for this section

Some problems with the MEV installations were identified during the construction review (e.g. the compressed flexi-duct connections to the air-valves), but there are likely to be other hidden issues that may be more difficult to identify and resolve. The housing industry has been raising concerns about the installation and commissioning of domestic mechanical ventilation systems for some time, and it is expected that changes to commissioning processes introduced in Part F 2010 will begin to address some of these issues. It is however suggested that MEV flow measurements are carried out so as to understand how widespread the problem of under-ventilation might be, and the nature of the causes.

The air permeability as measured by UCL at around $8m^3/h.m^2$ was higher than the nominal upper threshold of $5.0m^3/h.m^2$ generally considered for MEV systems to be most effective. Therefore, the underperformance of the MEV system will be, to some extent, compensated by uncontrolled air leakage via the fabric. The interrelationship between air-tightness and ventilation is an important factor in the design of low energy buildings, and it can be difficult to balance the need to maintain sufficient air exchange (for good internal air quality) with the contradictory requirement to minimise air leakage. It is unclear from the investigations at Centenary Quay to what extent the project team had considered this issue.

Measurements of primary temperatures to the HIU units in the test properties showed some unexpected variability in flow temperatures. Taken together with complaints from residents about slow heat up times (see BUS survey comments), this indicates that there remain some issues with the performance of the heating systems at Centenary Quay.

The potential for overheating at Centenary Quay may at some point require intervention. Possible options for reducing overheating would be to turn off the “keep-hot” facility in the HIUs or to provide additional insulation on primary pipework.

7 Monitoring methods and findings

Technology Strategy Board guidance on section requirements:	This section provides a summary breakdown of where the energy is being consumed, based around the first 6 months of metering results and other test results. Where possible, provide a simple breakdown of all major energy uses/producers (such as renewables) and the predicted CO_2 emissions. Explain how finding are affected by the building design, construction and use. This section should provide a review of any initial discoveries in initial performance in-use (e.g. after fine-tuning). If early stage interventions or adjustments were made post-handover, these should be explained here and any savings (or increases) highlighted. Does the energy and water consumption of the dwelling meet the original expectations? If not, explain any ideas you have on how it can be improved. Are there any unusual design features that have not been accounted for previously (e.g. grey water recycling pumps). Summarise with conclusions and key findings.

7.1 Description of in-use monitoring programme

The in-use monitoring programme at Centenary Quay consisted of the following studies:

- Detailed monitoring of energy and indoor environmental quality in Plots 118, 119 and 120.
- Review of the performance of the district heating system and CHP plant

Monitoring of Plots 118, 119 and 120 commenced in late January 2013. The residents of Plot 118 moved in mid-December 2012, those in Plot 119 moved in during the first week of April 2013 and the residents of Plot 120 moved in during the last week of April 2013. All houses were fully occupied and operational by the end of April 2013. Therefore, annual performance of these houses were analysed over the period 1 May 2013 to 30 April 2014. However, the monitoring team carried on collating the operational data until the end of August 2014. Explicit reference to the latest monitoring data will be made where noticeable change in energy performance or indoor environmental quality of these houses have been detected compared to the time period chosen for annual performance analysis.

The energy data for the district heating system and CHP plant was provided by E.ON (the ESCO managing the system) for the period October 2012 to July 2013, and was used to estimate the efficiency of communal boilers and the CHP plant.

7.2 Monitoring kit

The following parameters were monitored in Plots 118, 119 and 120:

- Indoor environment: Temperature, relative humidity (RH) and carbon dioxide levels in living rooms and bedrooms; temperature and relative humidity in bathrooms and toilets
- Energy used: Heating and electricity
- Ventilation system: airflow through all extracts located in wet rooms

In addition external conditions were monitored using a weather station that was installed on the main construction site. The following external parameters were monitored:

- Temperature and relative humidity
- Wind speed and wind direction
- Precipitation
- Barometric pressure
- Solar radiation

The kit that was installed in each property was supplied from ELTEK specialist data loggers as follows:

- RX250AL receiver logger with power supply and all connecting leads
- GSMSQ modem with antenna and lead to logger
- GW10 transmitter with built RH, temperature and CO_2 with AC power supply
- GD13E transmitter with display and input for a RH and temperature probe
- RHT 10D RH and temperature probe with 3M lead
- GC62 transmitters with 2 × pulse input for use with electricity meter and heat meter
- GS42 transmitter with 2 × pulse input for use with air flow sensors
- EE576 air flow sensors and AC power supply
- PRO1D electricity meter with pulse output. Din rail mounting.
- Heat meters Supercal 539

Data related to daily total space heating and hot water energy supplied to the Heat Interface Units (HIU) were also sourced from E.ON. This data were used to calculate the dwellings' hot water use by subtracting the metered heating from total heating and hot water energy supplied to HIU.

External conditions were recorded using a weather station that comprised the following:

- Vaisala WXT520 weather station (7 parameters) with pole top adaptor
- WBT pole mounting enclosure to house TMET transmitter

- Kipp and Zonen pyranometer type CMP3 measuring horizontal global radiation
- MP12U to power TMET and Vaisala WXT520 weather monitor

The monitoring kit was installed for each dwelling, and data collection started on the 23 January 2013 with 5 minutes recording frequency.

7.3 Data integrity

Prior to analysis, all datasets were checked for completeness and consistency. Where appropriate, spurious data points were removed and missing data were substituted with estimated values. In the case of the dwelling temperature, relative humidity and CO_2 concentrations, data transmissions to the Eltek data loggers were occasionally lost due to transmission clashes. These were often limited to one or two data points every week, and the missing data were readily substituted by data from the adjacent time period without affecting the integrity of the dataset or subsequent analysis. The dwellings' energy pulse data were unaffected by transmission clashes, as the data loggers use a cumulative pulse metering system. Any significant missing data are explicitly referenced in the subsequent parts of this section along with the method used to substitute the data or ensure the analysis is robust.

7.4 Weather conditions

Monthly mean, maximum and minimum temperatures from the on-site weather station at Centenary Quay are listed in Table 11, with time-series graphs of heating degree days, external temperature and external relative humidity shown in Figure 7, Figure 8, and Figure 9 respectively. Due to technical issues, external weather data for the period 6 December 2013 to 23 December 2013 were not recorded. The research team used the data reported by Southampton Weather website [1] to fill this gap and also sourced the heating degree days for December 2013 from Vesma [2].

The site peak summertime temperature in 2013 was 31.6 °C in July. The degree day data show that the winter of 2013-2014 was warmer than the 20 year mean for the south region reported by Vesma [2]. The total heating degree days for the period May 2013 to April 2014 was 1488 DD compared to 1915 DD for the 20-year mean.

Table 11 - Centenary Quay: Monthly External Temperatures and Degree Days

Month	Mean External Temperature (°C)	Standard Deviation (°C)	Maximum Temperature (°C)	Minimum Temperature (°C)	Heating Degree Days at 15.5 °C Base (DD)	Heating Degree Days South Region 20 Year Mean [2]
Feb-13	4.2	2.5	11.0	-0.7	315.8	276
Mar-13	4.3	2.9	12.8	-1.5	347.4	258
Apr-13	8.2	3.7	19.6	-0.5	221.2	192
May-13	11.6	3.2	21.9	3.8	126.8	115
Jun-13	15.1	3.1	24.9	7.6	42.9	54
Jul-13	19.4	4.1	31.6	10.4	7.8	27
Aug-13	18.1	2.8	27.6	11.9	8.2	23
Sep-13	15.4	3.2	28.6	7.4	38.9	48
Oct-13	14.1	3.0	20.8	4.7	61.3	109
Nov-13	8.3	3.0	16.0	0.1	217.3	205
Dec-13	6.6	2.6	12.0	-1.0	196 [2]	298
Jan-14	7.8	2.5	12.5	0.0	239.7	310
Feb-14	8.0	1.8	12.5	3.0	209.3	276
Mar-14	8.8	3.4	19.7	0.5	209.6	258
Apr-14	11.2	2.5	18.6	0.0	129.8	192
May-14	13.2	2.8	22.8	3.8	82.1	115
Jun-14	17.0	3.2	25.8	9.3	19.0	54

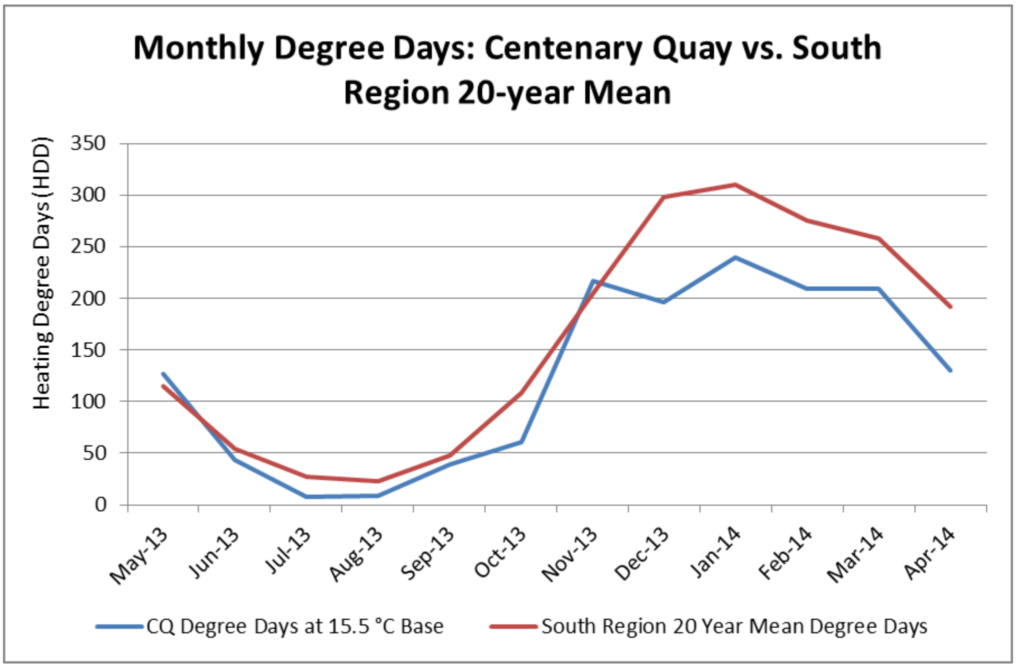


Figure 7 - Monthly Degree Days for Centenary Quay and South region 20-year mean

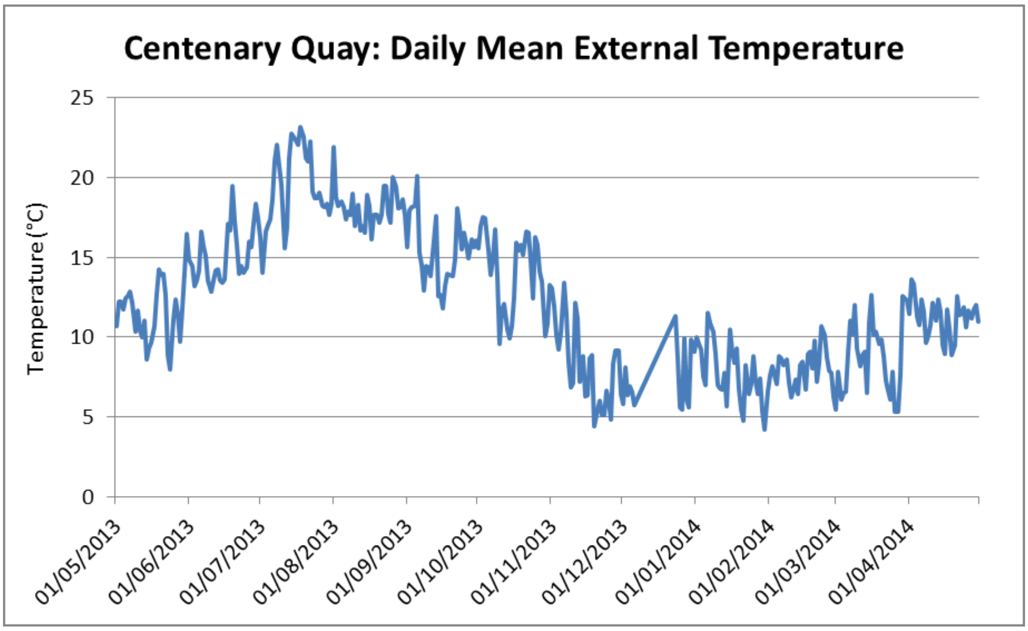


Figure 8 - Daily Mean External Temperature at Centenary Quay, May 2013-April 2014

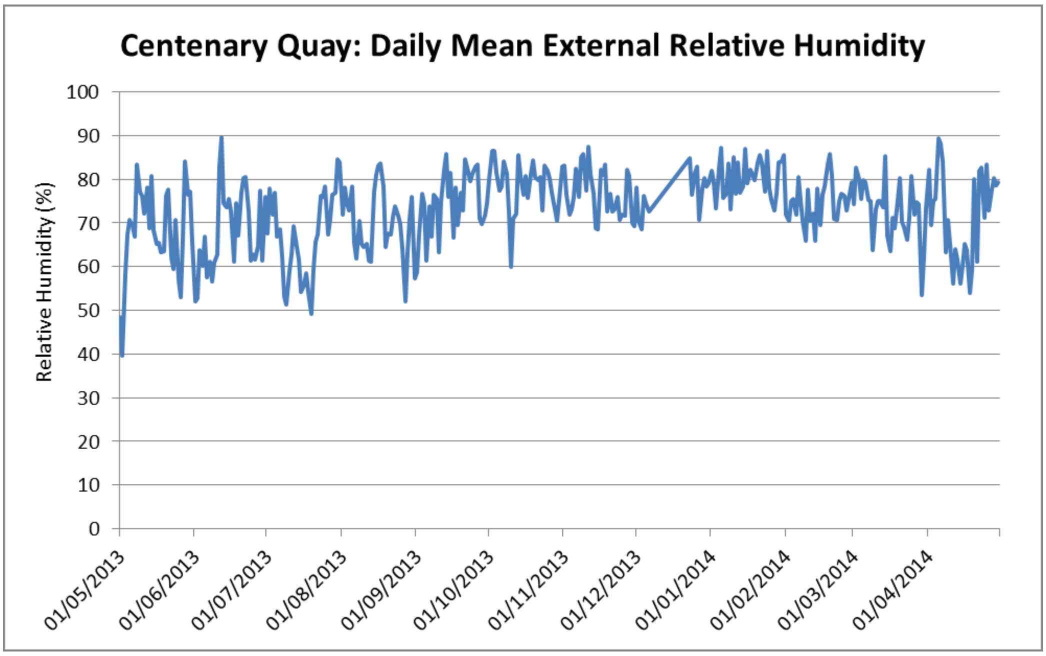


Figure 9 - Daily Mean External Relative Humidity at Centenary Quay, May 2013-April 2014

7.5 Thermal comfort conditions

Table 12-Table 14 summarise thermal comfort conditions recorded for the monitored dwellings over the period 1 May 2013 to 30 April 2014.

The minimum comfort temperature recommended for dwellings in CIBSE Guide A is 17-19 °C [3, p.16]. The respective midpoint of 18 °C was used as the first temperature threshold for thermal comfort analysis. CIBSE Guide A also specifies overheating threshold temperatures of 26 °C and 28 °C for bedrooms and living areas respectively [3, p.20]. These temperatures were used to define the other temperature bands used in Tables Table 12-Table 14. As for relative humidity, the acceptable comfort range within a room is 40%-70% with a risk of mould growth if the relative humidity stays at above 70% for a long period of time [3, p.287]. These thresholds were used to define relative humidity bands in Tables Table 12-Table 14 accordingly.

Table 12 - Thermal Comfort Conditions in Plot 118, 1 May 2013-30 April 2014

% of time thermal comfort conditions were within the given ranges						
Space Reference:		**Dining room**	**Living room**	**Bedroom 1**	**Bedroom 2**	**Bedroom 3**
Temperature (T)	< 18 °C	2.3%	0.0%	3.5%	1.4%	14.3%
	>= 18 °C & =< 26 °C	97.5%	97.4%	90.5%	95.1%	80.0%
	> 26 °C & =< 28 °C	0.2%	2.6%	5.0%	3.1%	4.2%
	> 28 °C	0.0%	0.0%	1.0%	0.4%	1.5%
Relative Humidity (RH)	< 40%	0.0%	0.0%	0.1%	0.1%	0.0%
	>= 40% & =<70%	97.9%	100%	99.6%	96.8%	98.5%
	> 70%	2.1%	0.0%	0.3%	3.1%	1.5%

The proportion of time temperature in Bedroom 3 of Plot 118 is below 18 °C seems a bit high. The CO_2 concentration data suggest this bedroom is less occupied than the other bedrooms in this dwelling; this may explain temperatures below 18 °C in this bedroom in winter.

Figure 10 shows daily mean temperatures in the monitored dwellings against the external temperature for the period 1 May 2013 to 30 April 2014. No data were recorded over the period 6 December 2013 to 23 December 2013. The straight lines in Figure 10 represent these missing data. The percentages reported in Table 12-Table 14 have been derived from available data points and therefore exclude the abovementioned periods in which data were missing.

Table 13 - Thermal Comfort Conditions in Plot 119, 1 May 2013-30 April 2014

% of time thermal comfort conditions were within the given ranges						
Space Reference:		**Dining room**	**Living room**	**Bedroom 1**	**Bedroom 2**	**Bedroom 3**
Temperature (T)	< 18 °C	28.5%	17.4%	28.5%	18.8%	26.2%
	>= 18 °C & =< 26 °C	71.4%	82.1%	69.8%	80.2%	71.3%
	> 26 °C & =< 28 °C	0.1%	0.5%	1.6%	1.0%	1.9%
	> 28 °C	0.0%	0.0%	0.1%	0.0%	0.6%
Relative Humidity (RH)	< 40%	0.1%	0.0%	0.5%	0.1%	0.7%
	>= 40% & =<70%	92.5%	95.1%	91.8%	87.5%	86.4%
	> 70%	7.4%	4.9%	7.7%	12.4%	12.9%

Figure 10 shows that mean internal temperatures are generally higher in Plot 118 than the other two dwellings. The mean internal temperatures are also higher in Plot 119 than Plot 120. Figure 11-Figure 16 show the variation of internal temperatures in different liveable spaces in the monitored dwellings in typical winter and summer days with 5 minutes frequency.

It appears that the occupants in Plot 118 tend to use higher heating set points. The temperature curves are also rather smooth and point to a stable and prolonged heating schedule. Plots 119 and 120, in contrast, use heating set points lower than Plot 118 with a spike in internal temperatures in the evening that reflects the time the heating system is programmed to kick in. Overall, the heating set points and schedules reflected on these graphs are consistent with the findings of the interviews reported in section 5. It is expected that space heating energy use in Plot 118 would be higher than Plots 119 and 120.

As for summertime temperatures, the graphs show that Plot 118 experiences higher internal temperatures than the other dwellings. The peak internal temperatures in Plot 118 bedrooms on 10 July 2013 were up to 3.5 °C higher than the peak external temperature, and exceeded the overheating threshold under the moderate external temperature of 25.1 °C (see Figure 12). Table 12 also shows that the percentage of time the bedrooms in Plot 118 experienced temperatures higher than 26 °C is significantly higher than the other dwellings. This will be further investigated in the overheating analysis.

Table 14 - Thermal Comfort Conditions in Plot 120, 1 May 2013-30 April 2014

% of time thermal comfort conditions were within the given ranges						
Space Reference:		**Dining room**	**Living room**	**Bedroom 1**	**Bedroom 2**	**Bedroom 3**
Temperature (T)	< 18 °C	41.7%	33.2%	39.9%	30.8%	45.2%
	>= 18 °C & =< 26 °C	57.9%	66.1%	57.1%	68.2%	52.0%
	>26 °C & =< 28 °C	0.4%	0.7%	2.6%	1.0%	2.3%
	> 28 °C	0.0%	0.0%	0.4%	0.0%	0.5%
Relative Humidity (RH)	< 40%	0.1%	0.1%	0.6%	0.3%	0.8%
	>= 40% & =<70%	89.7%	95.3%	91.4%	88.4%	86.5%
	> 70%	10.2%	4.6%	8.0%	11.3%	12.7%

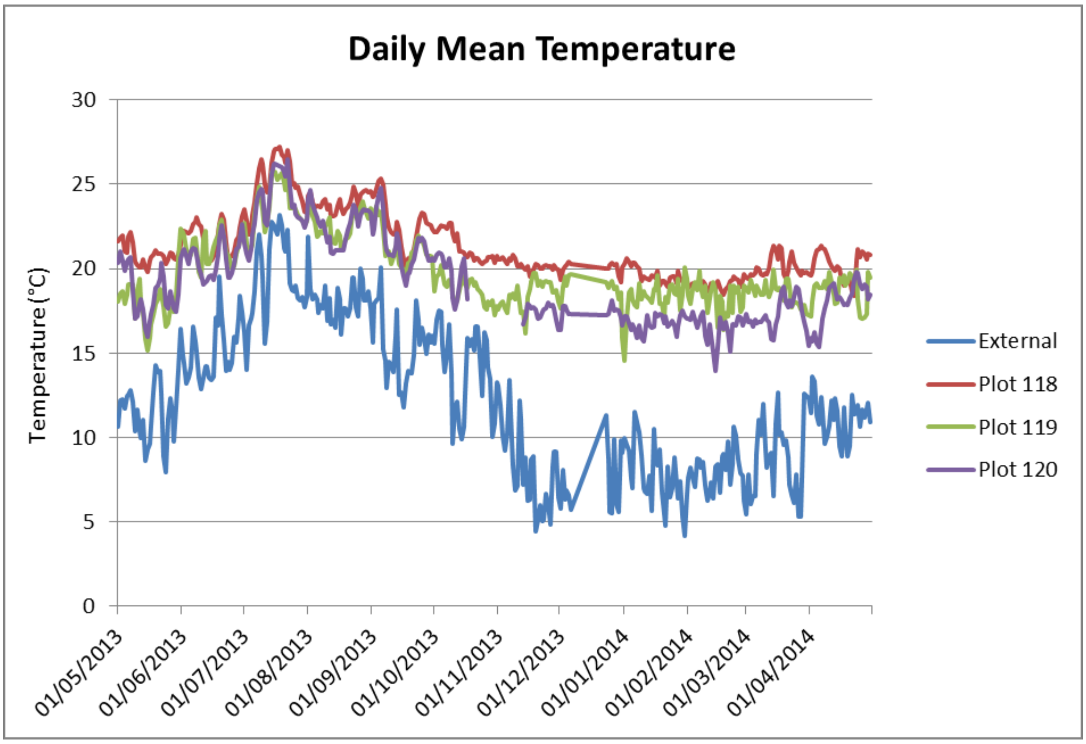


Figure 10 - Daily mean temperature in the monitored dwellings vs. external temperature

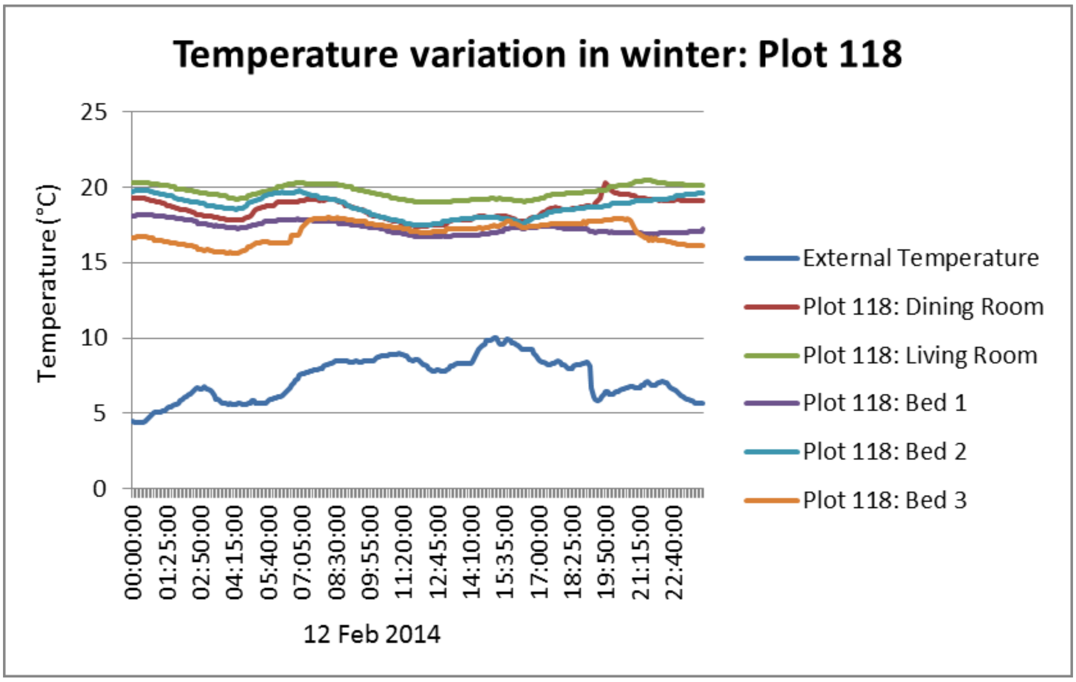


Figure 11 - Temperature variation in a typical winter day: Plot 118

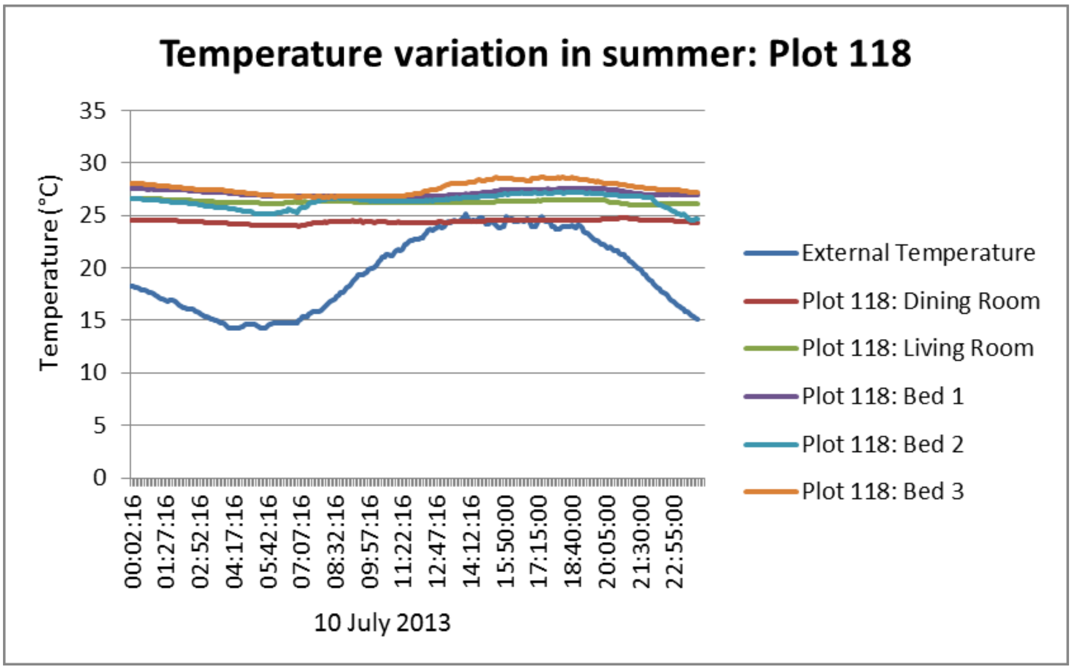


Figure 12 - Temperature variation in a typical summer day: Plot 118

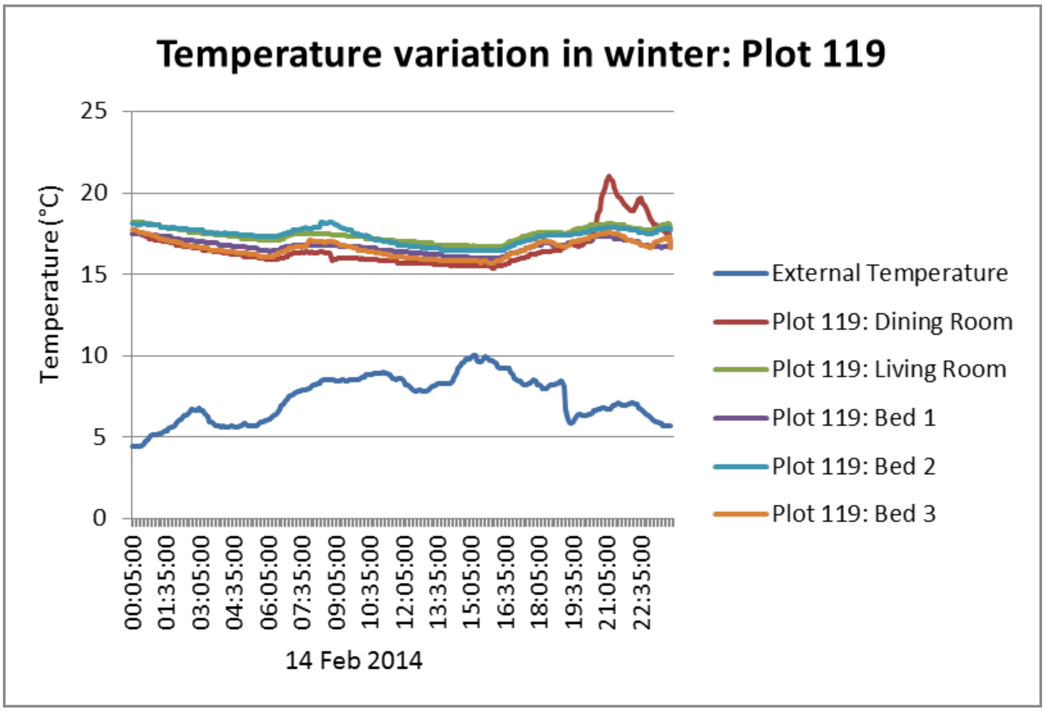


Figure 13 - Temperature variation in a typical winter day: Plot 119

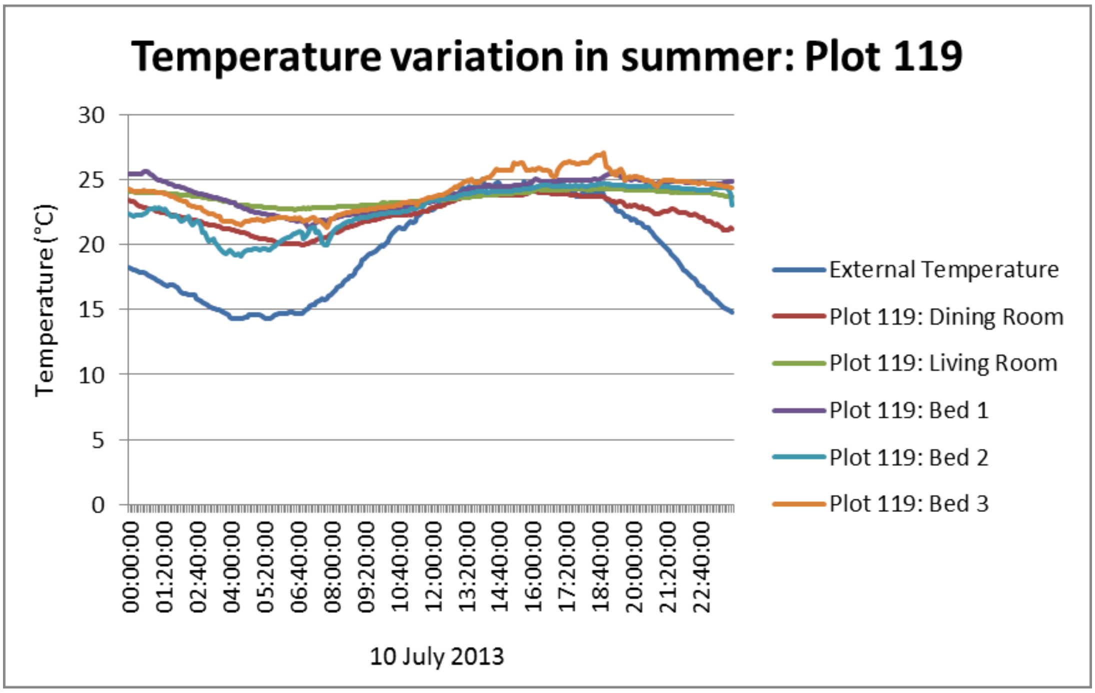


Figure 14 - Temperature variation in a typical summer day: Plot 119

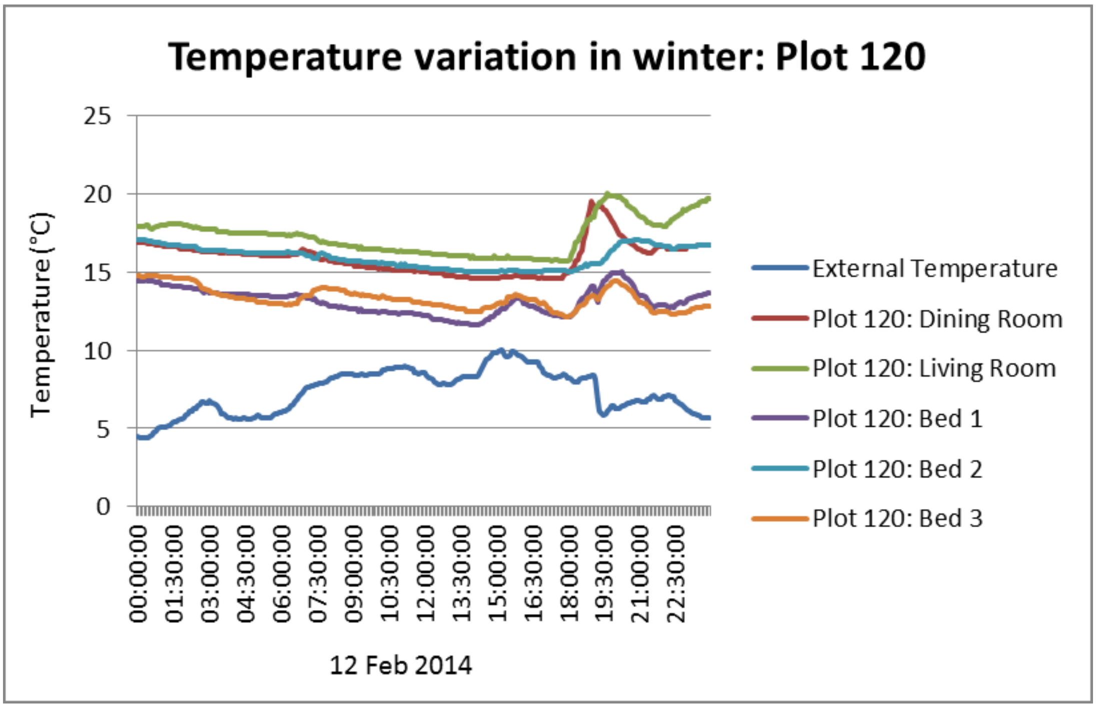


Figure 15 - Temperature variation in a typical winter day: Plot 120

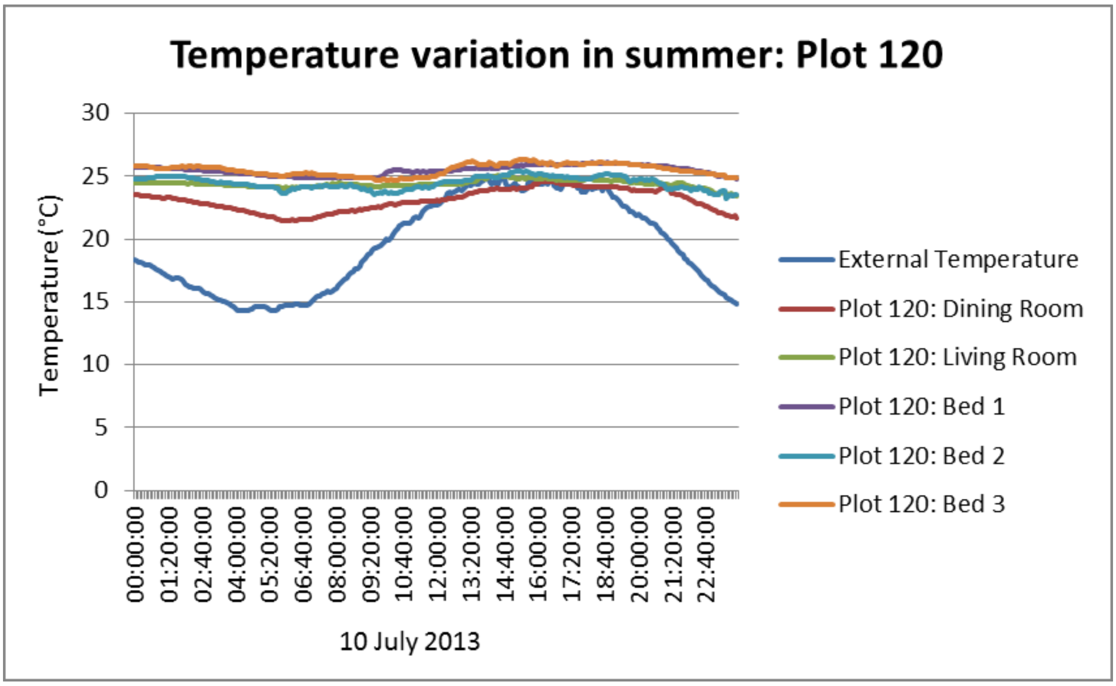


Figure 16 - Temperature variation in a typical summer day: Plot 120

Table 15 includes the mean temperatures and respective standard deviations for different liveable spaces in the monitored dwellings. The mean internal temperatures in Plot 118 in summertime were the highest, and in Plot 119 the lowest in all liveable spaces. The mean internal temperatures in Plot 118 were also the highest in winter in all liveable spaces, whereas Plot 120 had the lowest temperatures in winter in all liveable spaces. This consistent trend points to significant differences in occupants' behaviour in response to external temperatures.

Table 15 - Mean temperatures and respective standard deviations in the monitored dwellings

Time Period		Plot 118	Plot 119	Plot 120
May 2013 – September 2013	Dining Room	21.8 °C ± 1.8 °C	20.8 °C ± 2.4 °C	20.9 °C ± 2.2 °C
	Living Room	23.1 °C ± 1.7 °C	21.2 °C ± 2.3 °C	21.3 °C ± 2.0 °C
	Bedroom 1	23.6 °C ± 2.1 °C	21.1 °C ± 2.7 °C	22.1 °C ± 2.7 °C
	Bedroom 2	22.8 °C ± 2.0 °C	21.1 °C ± 2.2 °C	21.4 °C ± 2.1 °C
	Bedroom 3	23.4 °C ± 2.2 °C	21.4 °C ± 2.8 °C	21.5 °C ± 2.9 °C
October 2013 – April 2014	Dining Room	19.5 °C ± 0.9 °C	18.3 °C ± 1.3 °C	17.6 °C ± 1.2 °C
	Living Room	20.8 °C ± 0.9 °C	18.7 °C ± 1.1 °C	17.9 °C ± 1.2 °C
	Bedroom 1	20.1 °C ± 1.5 °C	18.2 °C ± 1.5 °C	17.3 °C ± 2.0 °C
	Bedroom 2	19.7 °C ± 0.9 °C	18.5 °C ± 1.1 °C	18.0 °C ± 1.2 °C
	Bedroom 3	19.3 °C ± 1.7 °C	18.4 °C ± 1.4 °C	16.9 °C ± 2.0 °C

A study of internal temperatures in 292 dwellings in Leicester reported mean living room temperature of 18.4 °C in February for all dwellings in the dataset [4]. Using this temperature as a benchmark for living room temperature in winter, it is notable that the mean internal temperature in Plot 118 living room in February 2014 was 20.4 °C. The mean internal temperature in Plot 119 living room in February 2014 was 18.5 °C, which is very close to the Leicester dataset. Finally, the mean internal temperature in Plot 120 living room in February 2014 was 17.6 °C. This helps to put the internal temperatures experienced in the monitored dwellings in the wider context of a large dataset of existing dwellings in the UK.

7.6 Carbon dioxide concentrations

A recent meta-analysis of peer reviewed research into the effects of ventilation and air quality suggests a CO_2 concentration level of around 900 ppm is a good indoor air quality proxy threshold above which research has shown there is statistically significant effect on human health [5]. Other sources provide an upper limit of 1,500 ppm for good indoor air quality [6]. Theses thresholds were used to analyse the CO_2 concentrations in the liveable spaces of the monitored dwellings. A CO_2 threshold of 500 ppm was also defined to identify the percentage of time background ventilation is close to external CO_2 concentrations.

Table 16-Table 18 provide the outcomes of this analysis for the monitored dwellings.

Table 16 - Carbon dioxide concentrations in Plot 118, 1 May 2013-30 April 2014

% of time CO_2 concentrations were within the given ranges						
Space Reference:		**Dining room**	**Living room**	**Bedroom 1**	**Bedroom 2**	**Bedroom 3**
CO_2 concentration (ppm)	< 500 ppm	2.8%	4.8%	0.0%	4.7%	5.8%
	>= 500 ppm & < 900 ppm	95.1%	79.5%	85.6%	65.7%	89.6%
	>= 900 ppm & <1500 ppm	2.0%	14.0%	14.0%	22.0%	4.0%
	>= 1500 ppm	0.1% (Max: 2710 ppm)	1.7% (Max: 3073 ppm)	0.4% (Max: 2822 ppm)	7.6% (Max: 2864 ppm)	0.6% (Max: 2785 ppm)

Apart from bedroom 2 in Plot 120, which experienced CO_2 concentrations above 1500 PPM for almost 30% of the monitoring period with a maximum concentration level of 3,850 ppm, the CO_2 concentration levels in all other liveable spaces remained below 1,500 for more than 90% of the time.

As explained in Section 5, occupants in Plot 118 closed the window trickle vents in winter, while occupants in Plots 119 and 120 blocked the trickle vents with paper blinds. This has contributed to occasional high CO_2 levels in all monitored dwellings especially in winter. The comments received from the occupants revealed that they were not entirely aware of the significance of window trickle vents in maintaining acceptable level of indoor air quality in winter. It is recommended that this is more specifically covered in home user guides and home demonstrations for the future projects.

Table 19 provides the mean CO_2 concentrations and respective standard deviations in the monitored dwellings over the measurement period.

While the CO_2 concentration levels point to a good level of indoor air quality in the monitored dwellings for most of the time, it is notable that the concentration levels have increased since the start of the monitoring programme in all monitored dwellings (Figure 17-Figure 19). Figure 20 extends the presentation of the daily mean CO_2 concentration levels from the main monitoring period of 1 May 2013 – 30 April 2014 to the end of June 2014 to ensure the observed increase in the CO_2 concentrations is not merely a seasonal effect. While the CO_2 levels seem to have been stabilised a bit in the summer of 2014, it is notable that the daily mean CO_2 concentrations in June 2014 are 100-200 ppm higher than June 2013. The increase in the CO_2 levels is more pronounced in Plot 119 which might relate to higher number of occupants and frequent visitors (see Section 5). However, even the background CO_2 concentration levels represented by daily minimum concentrations show similar trends (Figure 21). One should be cautious in interpreting these trends as these might merely reflect calibration issues with the CO_2 sensors. However, if these measurements reflect the actual concentration levels, this increase in CO_2 levels could point to under-ventilation of the monitored dwellings. The evidence collated from other physical measurements has been used to further investigate this issue (see 7.8 and 7.9).

Table 17 - Carbon dioxide concentrations in Plot 119, 1 May 2013-30 April 2014

% of time CO_2 concentrations were within the given ranges						
Space Reference:		**Dining room**	**Living room**	**Bedroom 1**	**Bedroom 2**	**Bedroom 3**
CO_2 concentration (ppm)	< 500 ppm	0.1%	6.4%	19.7%	8.7%	46.9%
	>= 500 ppm & < 900 ppm	75.2%	81.5%	64.7%	65.6%	48.8%
	>= 900 ppm & <1500 ppm	24.4%	8.4%	14.6%	20.7%	4.3%
	>= 1500 ppm	0.3% (Max: 2285 ppm)	3.7% (Max: 2456 ppm)	1.0% (Max: 2097 ppm)	5.0% (Max: 3273 ppm)	0.0%

Table 18 - Carbon dioxide concentrations in Plot 120, 1 May 2013-30 April 2014

% of time CO_2 concentrations were within the given ranges						
Space Reference:		**Dining room**	**Living room**	**Bedroom 1**	**Bedroom 2**	**Bedroom 3**
CO_2 concentration (ppm)	< 500 ppm	7.3%	8.8%	53.1%	0.4%	22.0%
	>= 500 ppm & < 900 ppm	86.4%	84.4%	44.8%	37.7%	69.2%
	>= 900 ppm & <1500 ppm	5.8%	5.5%	1.5%	32.5%	7.5%
	>= 1500 ppm	0.5% (Max: 3643 ppm)	1.3% (Max: 2857 ppm)	0.6% (Max: 2472 ppm)	29.4% (Max: 3850 ppm)	1.3% (Max: 2809 ppm)

Table 19 - Mean carbon dioxide concentrations

Time Period	Plot 118 (PPM)	Plot 119 (PPM)	Plot 120 (PPM)
May 2013 – Sept 2013	694 ± 71	602 ± 74	657 ± 84
Oct 2013 – April 2014	774 ± 93	803 ± 118	829 ± 86

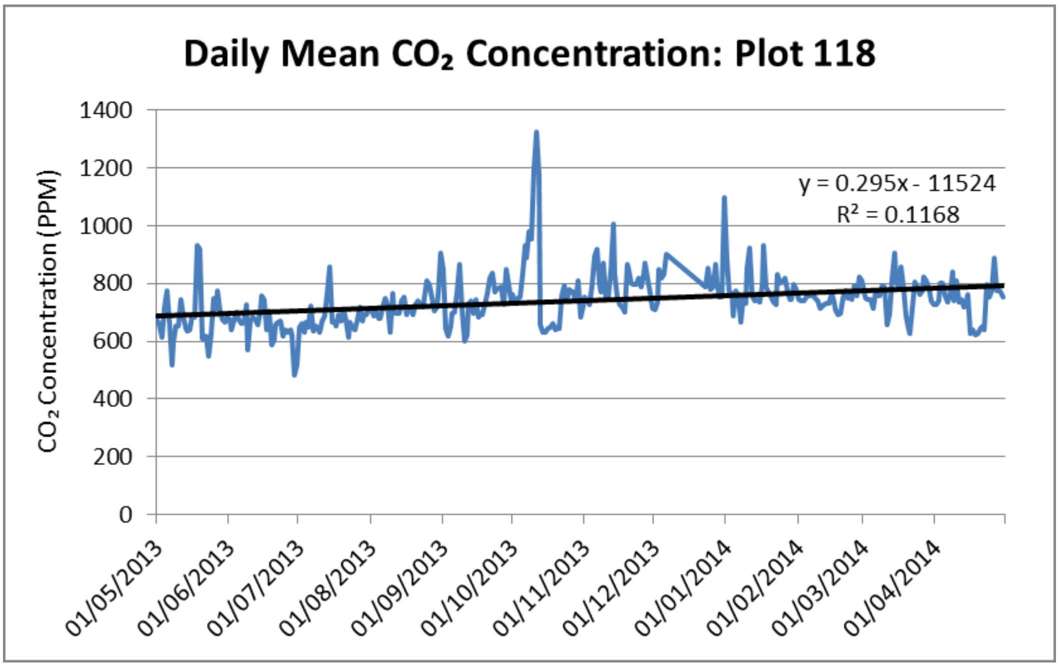


Figure 17 - Daily mean CO_2 concentration in Plot 118

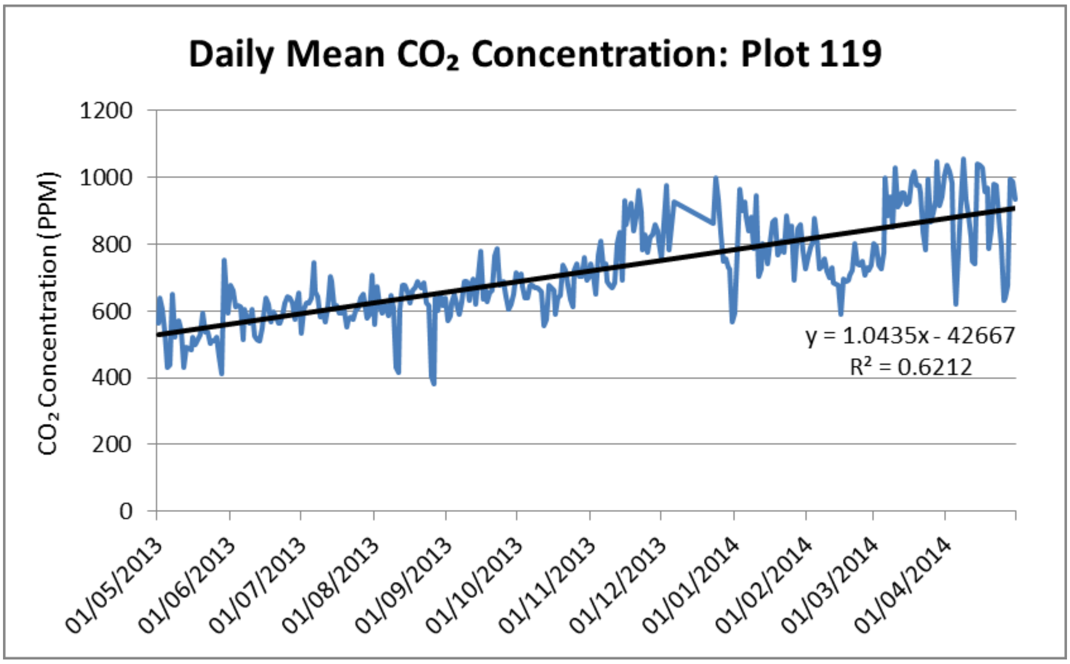


Figure 18 - Daily mean CO_2 concentration in Plot 119

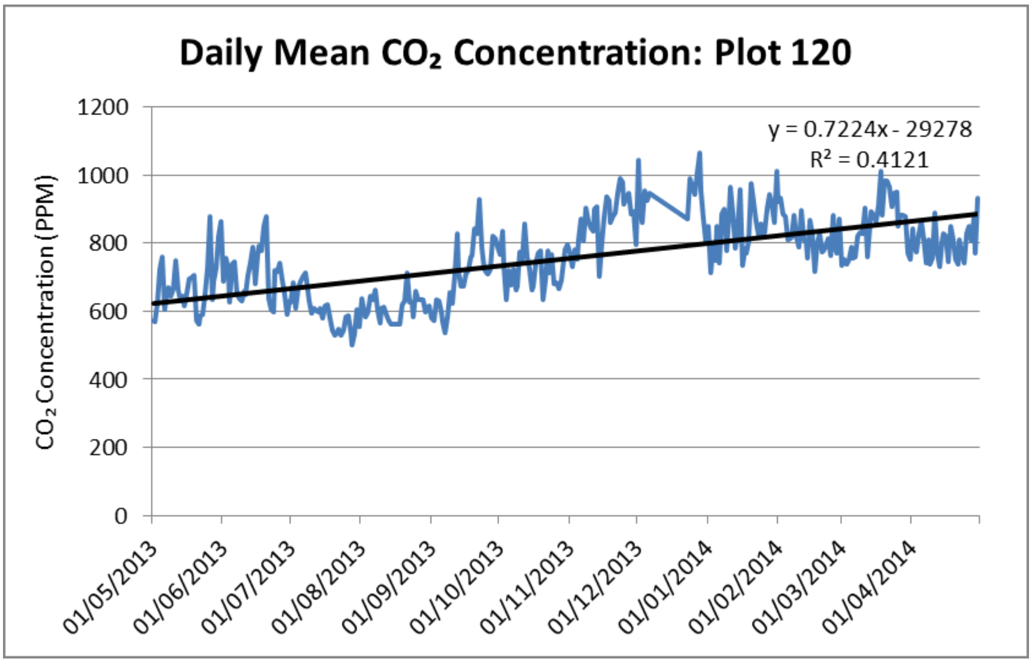


Figure 19 - Daily mean CO_2 concentration in Plot 120

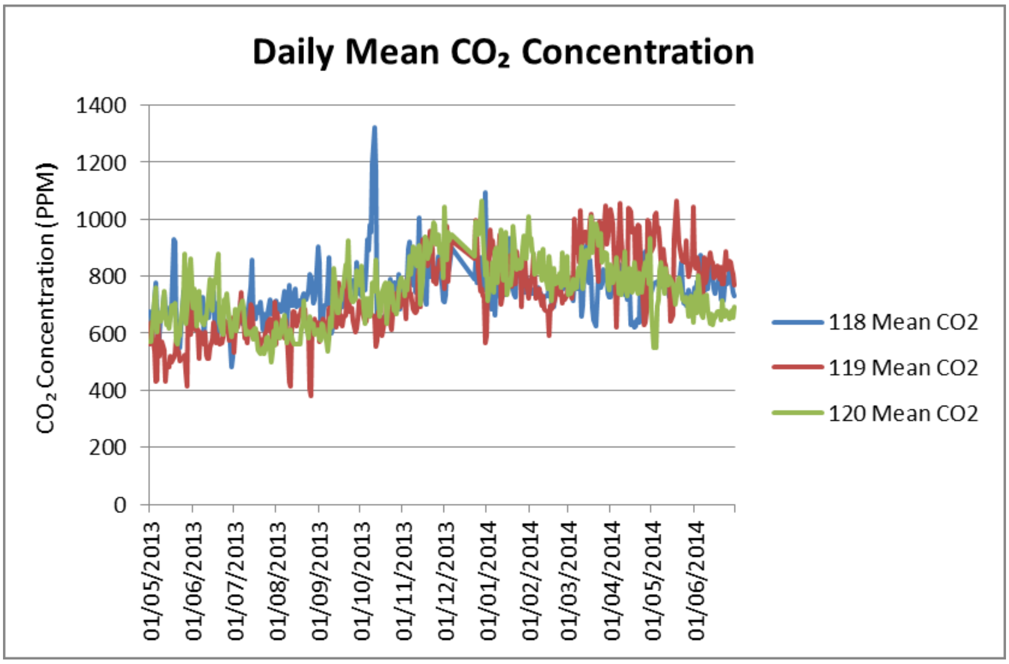


Figure 20 - Daily mean CO_2 concentration in the monitored dwellings until June 2014

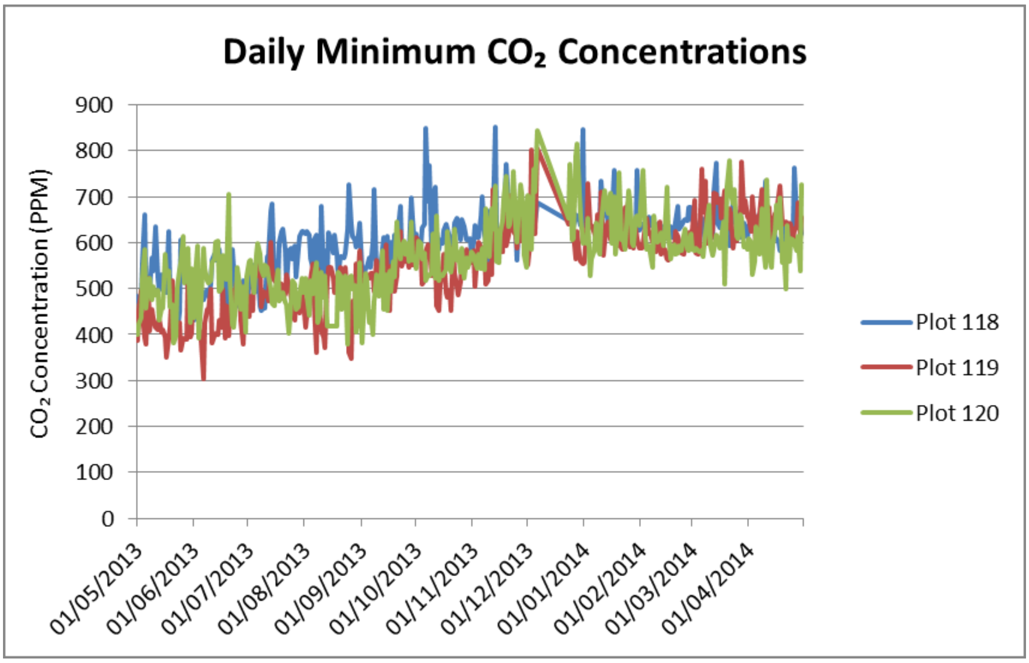


Figure 21 - Daily minimum CO_2 concentrations in the monitored dwellings

7.7 Overheating Analysis

CIBSE Guide A defines the overheating peak temperatures of 26 °C for bedrooms and 28 °C for living areas in a dwelling, with maximum 1% annual *occupied* hours above these temperatures as the overheating criterion [3, p.20].

The analysis of thermal comfort conditions revealed that dining rooms and living rooms of the monitored dwellings did not experience temperatures above 28 °C over the measurement period of 1 May 2013 to 30 April 2014 (Tables Table 12-Table 14). However, temperatures in all bedrooms exceeded 26 °C for some time. Table 20.A includes the percentages of time bedroom temperatures exceeded 26 °C with no correction for occupancy. It can be seen that apart from Bedroom 2 in Plots 119 and 120 all other bedrooms exceeded the overheating temperature.

CO_2 concentrations in bedrooms could be used as a proxy for occupancy. Allowing for the increase detected in background CO_2 concentrations (Figure 21), a conservative background threshold of 800 ppm was chosen for overheating analysis. If the bedrooms CO_2 levels are higher than 800 ppm, it is highly likely that the bedrooms are occupied. Therefore, the respective data points must be included in the overheating analysis. Table 20.B shows the outcome of this analysis. Temperatures in bedroom 1 (i.e. second floor bedroom) exceed CIBSE overheating criterion in all monitored dwellings. Temperatures in bedrooms 2 & 3 of Plot 118 also exceed the overheating criterion albeit not to the extent of bedroom 1.

It should also be noted that the weather file recommended by CIBSE Guide A for overheating analysis is the CIBSE Design Summer Years (DSYs). The Design Summer Years are meant to provide a more stringent test of overheating risk than the Test Reference Years (TRYs) that usually are used for energy performance calculations. The recorded weather data show that the summer of 2013 was not a particularly hot summer; while the maximum temperature in July 2013 reached 31.6 °C, maximum temperatures in June and August 2013 were 24.9 °C and 27.6 °C respectively. It is therefore certain that the 'as-operated' bedrooms would not pass CIBSE overheating criterion if subjected to the respective Design Summer Years weather file for Southampton.

Table 20 - Overheating analysis of the monitored dwellings: CIBSE Guide A method

A. **% of time temperature is higher than 26 °C**			
Dwelling	**Bedroom 1**	**Bedroom 2**	**Bedroom 3**
Plot 118	6.0%	3.5%	5.7%
Plot 119	1.7%	1.0%	2.5%
Plot 120	3.0%	1.0%	2.8%
B. **% of *occupied* time temperature is higher than 26 °C** Proxy used for occupancy: CO_2 concentration above 800 PPM			
Dwelling	**Bedroom 1**	**Bedroom 2**	**Bedroom 3**
Plot 118	7.4%	1.6%	1.5%
Plot 119	1.3%	0.1%	0.0%
Plot 120	5.0%	0.1%	0.3%

The as-built SAP calculations report that the overheating risk of the monitored dwellings is 'Not significant'. SAP overheating calculations are carried out in accordance with the procedure included in SAP Appendix P [7]. The overheating risk categories derived from this procedure are based on calculated mean internal temperature for the whole dwelling during the summer period relative to the mean external temperature quoted for the respective geographic region. The 'Not significant' overheating risk category for the South region corresponds to a temperature difference less than 4.5 °C between the summertime mean internal temperature and the mean external temperature [7, p.80].

SAP Appendix P procedure could be applied to the monitored dwellings using the actual data recorded for the dwellings (Table 21).

Table 21 - Overheating analysis of the monitored dwellings: SAP Appendix P

Plot	Mean internal temperature (June - August 2013)	Mean external temperature (June-August 2013)	Temperature difference	SAP 2005 overheating risk (as-operated)	SAP 2005 overheating risk (as-built)
Plot 118	23.6 °C	17.6 °C	6.0 °C	Medium (6.0 °C =< Delta T < 7.5 °C)	Not significant (Delta T <4.5 °C)
Plot 119	22.5 °C	17.6 °C	4.9 °C	Slight (4.5 °C =< Delta T < 6.0 °C)	Not significant (Delta T <4.5 °C)
Plot 120	22.3 °C	17.6 °C	4.7 °C	Slight (4.5 °C =< Delta T < 6.0 °C)	Not significant (Delta T <4.5 °C)

Table 21 shows that the risk of overheating in all monitored dwellings is higher than what was predicted in the as-built calculations. However, according to SAP Appendix P, the risk of overheating in none of the dwellings is 'High' which corresponds to a temperature difference of equal or higher than 7.5 °C between mean internal temperature and mean external temperature over the summer period.

Comparing the outcomes of overheating analysis carried out using CIBSE Guide A and Appendix P of SAP, it is clear that CIBSE Guide A provides more stringent and robust overheating criteria. CIBSE Guide A method is dependent on annual temperatures rather than summertime mean temperatures and is more refined; it takes into account the difference between liveable spaces rather than relying on a single mean temperature for the whole dwelling. There are lessons to be learned here in terms of overheating analysis for the future projects in the context of expected increases in external temperatures as a result of climate change.

Overall, all monitored dwellings show higher risk of overheating than the as-built calculations using SAP methodology, with evidence of overheating in some bedrooms when the more stringent criteria of CIBSE Guide A are applied.

Crest Nicholson has put in place several processes to assess the potential for overheating and mitigate it where necessary. All sites and scheme designs are reviewed in detail by the Group Technical Director and where there is a reasonable level of risk for overheating (e.g. designs that have high levels of glazing, single-sided apartments, low thermal mass construction etc.), Crest Nicholson will undertake dynamic modelling. Designs are assessed based on the CIBSE guidance, but in contrast to the CIBSE protocol the results are assessed against a range of transition zones for overheating triggers, rather than a single trigger zone. In Crest Nicholson's view, the CIBSE Standard is too rigid and narrow.

The range of triggers and responses Crest Nicholson has developed are:

- Where the temperature requirement is not exceeded by more than 0.8% of annual occupied hours then no action is required

- Where the temperature requirement is exceeded by 0.81-1.19% of annual occupied hours, then precautionary action must be taken. This could be lowering g-values of windows, considering ventilation rates to increase air changes, introducing integral blinds or shutters, looking at solar shading options such as trees, pre-wiring for future installation of comfort cooling

- Where the temperature requirement is exceeded by 1.20% of annual occupied hours then the dwelling must have some formal design change to reduce the overheating time to an acceptable level. This could include changing window specification (g-value or reflective membrane/coatings), solar shading (brisole or similar), shutters, installing comfort cooling to key rooms, etc.

7.8 MEV performance

In order to check the performance of the MEV systems, the extract flow rates from the diffuser vents in the monitored dwellings were measured in trickle and boost modes using a calibrated Testo 417 anemometer and flow capture hood in Phase 1 of the project. Table 12 compares the results of these measurements with the design specifications. While the design boost flows were not generally met, the measured trickle flows were, in particular, significantly lower than the design specification in all dwellings.

Table 22 - Measured total extract flow rates for the monitored dwellings

Plot	Design Trickle Flow (l/s)	Measured Trickle Flow (l/s)	Design Boost Flow (l/s)	Measured Boost Flow (l/s)
Plot 118	30.4	11.7	35.0	34.9
Plot 119	30.4	12.2	35.0	30.2
Plot 120	30.4	2.2	35.0	24.1

The flow rates inferred from the EE576 air velocity transmitters, installed in the ductworks as part of the monitoring kit, show a rapid decline in MEV flow rates in Plot 118 in the first six months of the monitoring programme (Figure 22). The exact root cause for the decline in the MEV flow rates is unknown, but could, for example, be due to a problem with the fan unit or build-up of dust in the ducts and air valves.

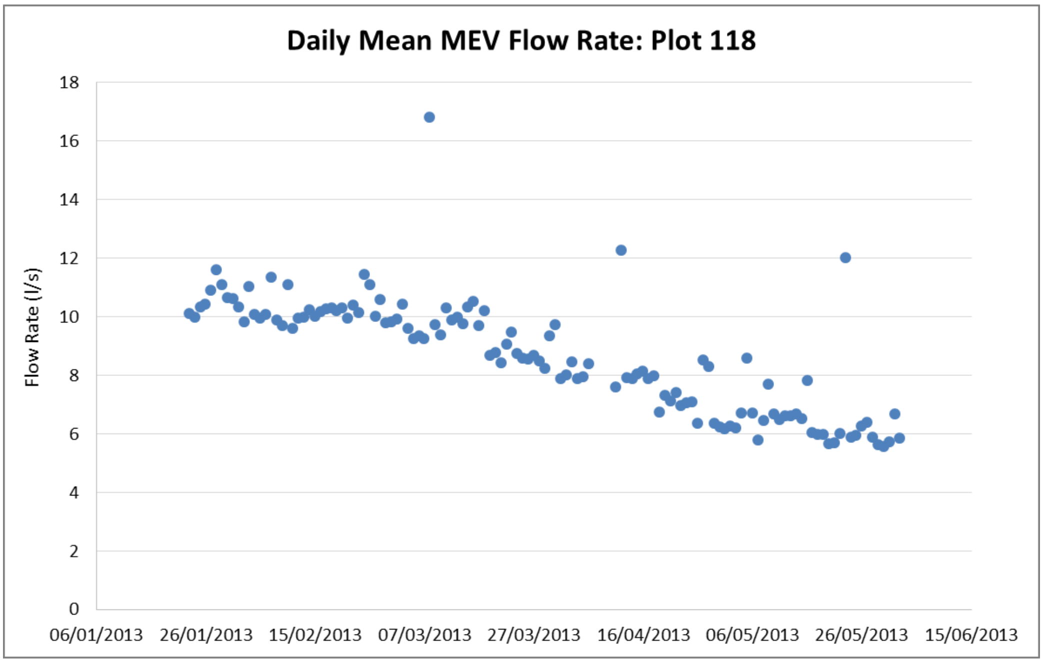


Figure 22 - Daily mean MEV flow rate in Plot 118

The monitoring data shows that Plot 118 and Plot 120 total MEV flow rates are significantly lower than design specification in both trickle and boost modes. Total MEV flow rate in Plot 119 is slightly higher than the design trickle mode but lower than the design boost mode. The continuous flow rate inferred for the kitchen and ground floor toilet in Plot 119 is around 14 l/s that is actually higher than the design specifications of 11.3 l/s for the kitchen and 5.2 l/s for the toilet. However, the bathroom flow rates are significantly lower than the minimum design flow rate of 7 l/s. The flow rates in the kitchens and all wet rooms of Plots 118 and 120 are also lower than the minimum design specifications.

The recorded data show that there was a physical intervention to improve the performance of the MEV system in March 2014. Figure 23 shows the total MEV flow rates before and after this intervention that led to slight improvement in the performance of the MEV system in Plot 118 and also increased the minimum flow rate in Plot 120. However, total flow rates in Plots 118 and 120 and the flow rates in Plot 119 bathrooms remain below minimum design flow rates.

Figure 24 shows the stable performance of the MEV systems in June 2014 with significant underperformance in Plots 118 and 120. Total performance of Plot 119 is better due to higher than design flow rates recorded in the kitchen and ground floor toilet. However, both first and second floor bathrooms are significantly under-ventilated. Figure 25 shows the variation of relative humidity in the 1st floor bathroom of Plot 119. It takes almost 10 hours for the RH to come back to its baseline after it reaches its peak of 90%.

Overall, both the measurements taken in Phase 1 with calibrated anemometer and flow capture hood, and also the continuous measurements taken by EE676 probes point to significant shortcomings in the MEV systems' performance in the monitored dwellings.

As a result of the Phase 1 performance test and Phase 2 monitoring data, Crest Nicholson is undertaking further research into the MEV system at one of the three monitored homes to understand whether certain interventions, such as introducing a humidstat, make any difference to the system and conditions within the home. This programme of monitoring will happen over one year, at Crest Nicholson's expense.

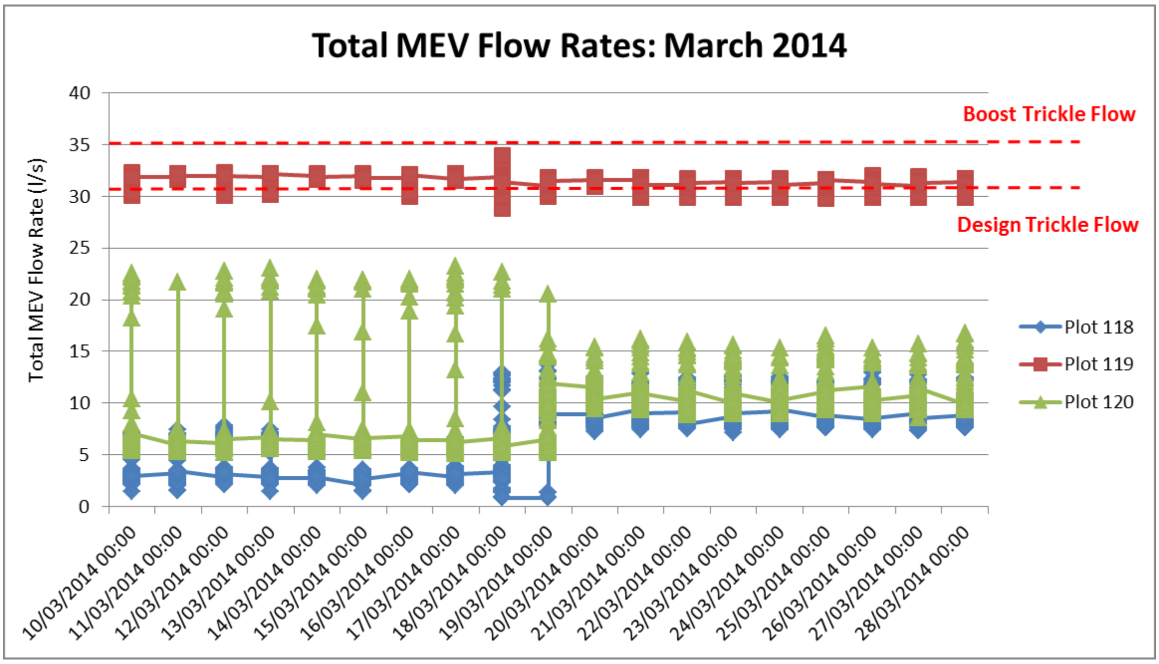


Figure 23 - Total MEV flow rates in the monitored dwellings, March 2014

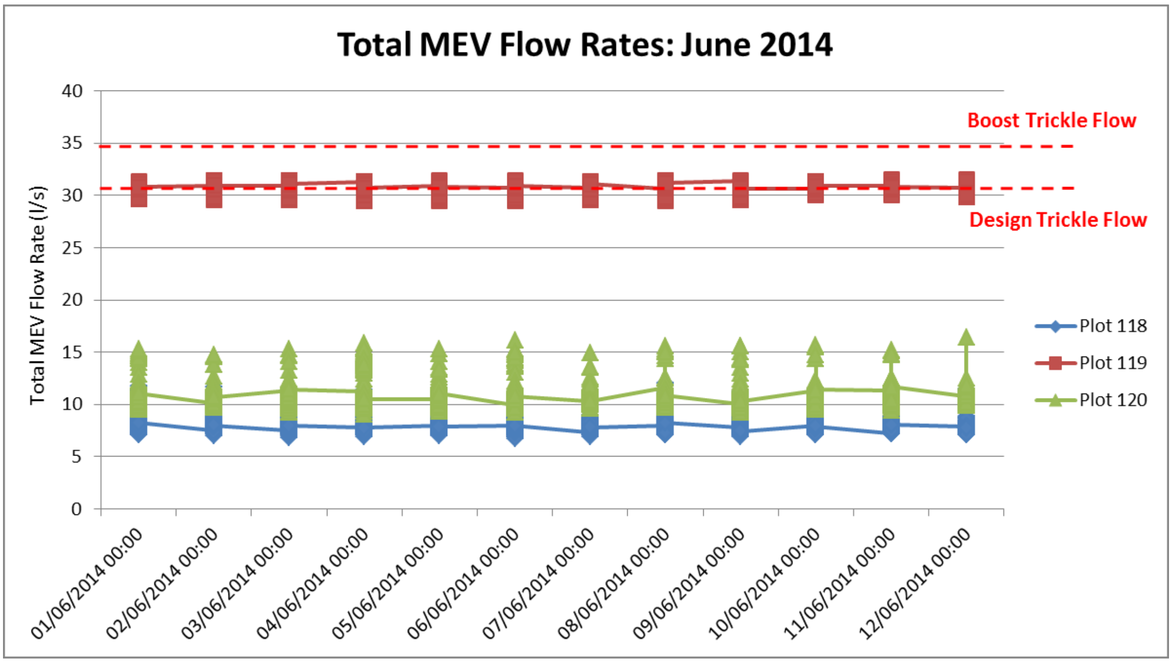


Figure 24 - Total MEV flow rates in the monitored dwellings, June 2014

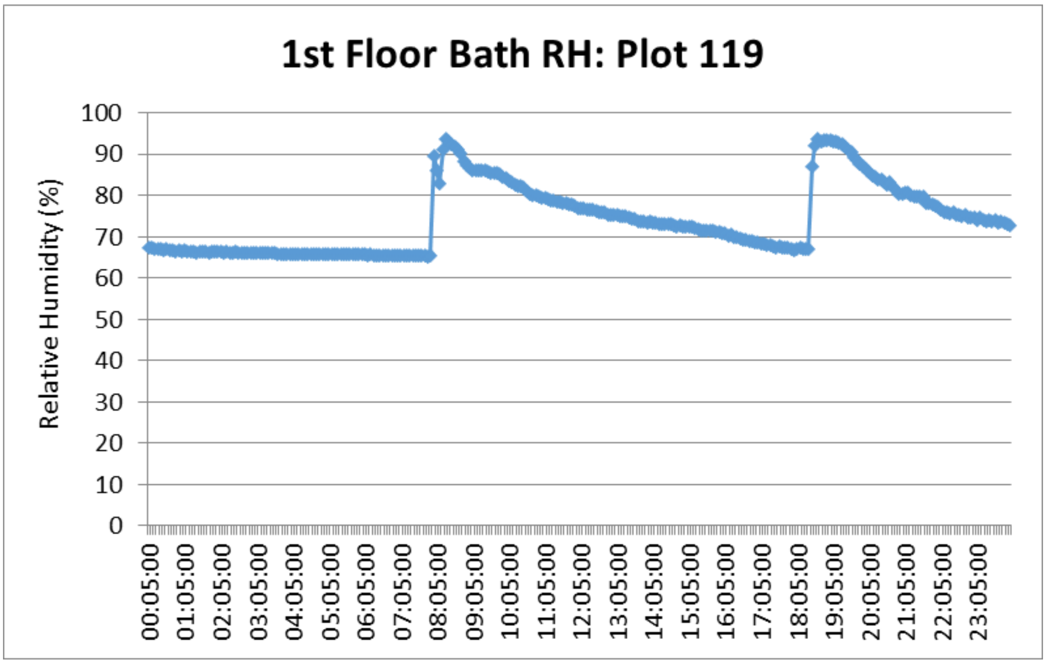


Figure 25 - Variation of relative humidity in the1st floor bathroom in Plot 119, 4 June 2014

7.9 Energy performance: electricity use

The disaggregated electricity consumption for cooking, lighting, appliances and the MEV fan shows differences in usage patterns between the three monitored dwellings as shown in Table 23.

All electricity end-uses were sub-metered. However, some data were missing from the kitchen and appliances' sub-meters in Plot 118 during the measurement period due to malfunctioning transmitters. These transmitters were replaced on the 17th of July 2014, and the latest energy data acquired for cooking and appliances along with the utility bills for May 2013- April 2014 were used to estimate the electricity use of cooking and appliances in Plot 118. The sub-metered electricity use data in Plots 119 and 120 were also compared against the utility bills to ensure the sub-metered data are robust. The total electricity uses sub-metered over the annual measurement period were within 2% and 5% of the electricity use reported on the utility bills of Plots 119 and 120 respectively.

Electricity use of all monitored dwellings is lower than 3,300 kWh/annum reported for typical UK dwelling by OFGEM [8]. However, while total electricity use of Plots 118 and 120 are almost on a par, electricity use of Plot 119 is significantly higher. Excess in cooking, lighting and appliances' electricity use could, to some extent, be related to the higher number of regular occupants in this dwelling. However, the significant discrepancy between the MEV fan energy use in this unit and the other dwellings is notable. This discrepancy cannot be fully explained by differences in flow rates depicted in Figure 23 and Figure 24. The manufacturer's quoted specific fan power for the MEV system is 0.17 W/l/s. This yields an annual upper limit of 52.1 kWh for electricity use of the MEV system allowing for the design boost flow rate of 35 l/s. The boost flow rate of the MEV fan in Plot 119 is actually lower than the design intent of 35 l/s and the system is operating in trickle mode most of the time. The sub-metered electricity use of the MEV system in Plot 119 is, therefore, indicative of a specific fan power that is significantly higher than the design intent.

Table 23 - Electricity consumption in the monitored dwellings, 1 May 2013-30 April 2014

Electricity	Plot 118	Plot 119	Plot 120
Cooking (kWh)	548.7	1039.0	990.3
Lighting (kWh)	208.0	504.4	99.4
Appliances (kWh)	679.3	990.9	305.9
MEV Fan (kWh)	31.9	216.6	29.6
TOTAL (kWh/a)	1467.9	2751.9	1425.2
TOTAL (kWh/day)	4.0	7.5	3.9

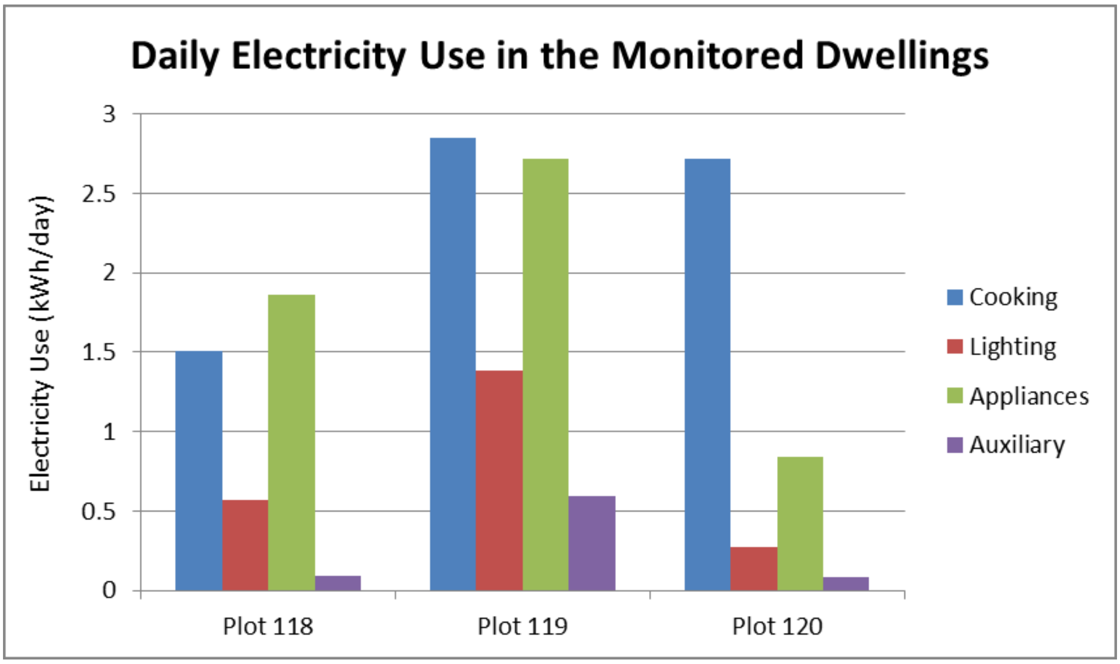


Figure 26 - Daily electricity use in the monitored dwellings

7.10 Energy performance: space heating energy

The monthly space heating energy use for the monitored dwellings is provided in Table 24. Heating energy use varies significantly between the dwellings. This reflects the different set points used by the occupants, different operating hours, and the way they operate the windows. Occupants in Plot 118 tend to use higher heating set points with longer operating hours. Based on the interviews with the occupants, it appears that the occupants in Plot 119 are more likely to open the windows in winter. Occupants in Plot 120, on the other hand, tend to use lower heating set points and shorter heating schedules.

As annual heating data is available for the monitored dwellings, it is possible to determine the empirical Base Temperature for these dwellings and compare it with the base temperature used in the as-built SAP. Base temperature is the threshold mean external temperature for operation of heating system in a dwelling. The theoretical base temperature calculated in as-built SAP assessment for the monitored dwellings was 10.9 °C. Figure 27-Figure 29 show the daily space heating energy against recorded daily mean external temperatures for the monitored dwellings. The empirical base temperatures derived for Plots 118, 119 and 120 are 15.4 °C, 14.7 °C and 14.1 °C respectively.

Theoretical base temperature is sensitive to uncertainties in internal temperature set points and internal gain in addition to the heat loss parameter. Yet the empirical base temperatures in the three dwellings (with inherent differences in internal set points and gains) are significantly higher than the theoretical base temperature. They are also close to the 15.5 °C base temperature used for heating degree day analysis of the existing building stock in the UK; whereas lower base temperature is expected for these new build dwellings. This is, to a large extent, the consequence of higher than expected heat loss parameters in these dwellings, which was uncovered in the Phase 1 of the Building Performance Evaluation.

Table 24 - Space heating energy use in the monitored dwellings

Month	Plot 118	Plot 119	Plot 120
Feb-2013	1004	-	-
Mar-2013	1190.7	-	-
Apr-2013	612.2	642.8	-
May-2013	337	129.9	102
Jun-2013	30.1	233.7	0.7
Jul- 2013	0.8	0.7	0.8
Aug-2013	0.8	0.7	0.8
Sep-2013	8.4	53.9	0.9
Oct-2013	168.4	140.3	0.9
Nov-2013	626	648.7	248.9
Dec-2013	727.8	605.3	312.7
Jan-2014	852	938.6	411.8
Feb-2014	889.8	810.9	390.8
Mar-2014	556.0	378.7	106.5
Apr-2014	252.0	213.9	21.9
May-2014	168.2	114.3	18.6
Jun-2014	0.7	0.7	0.7

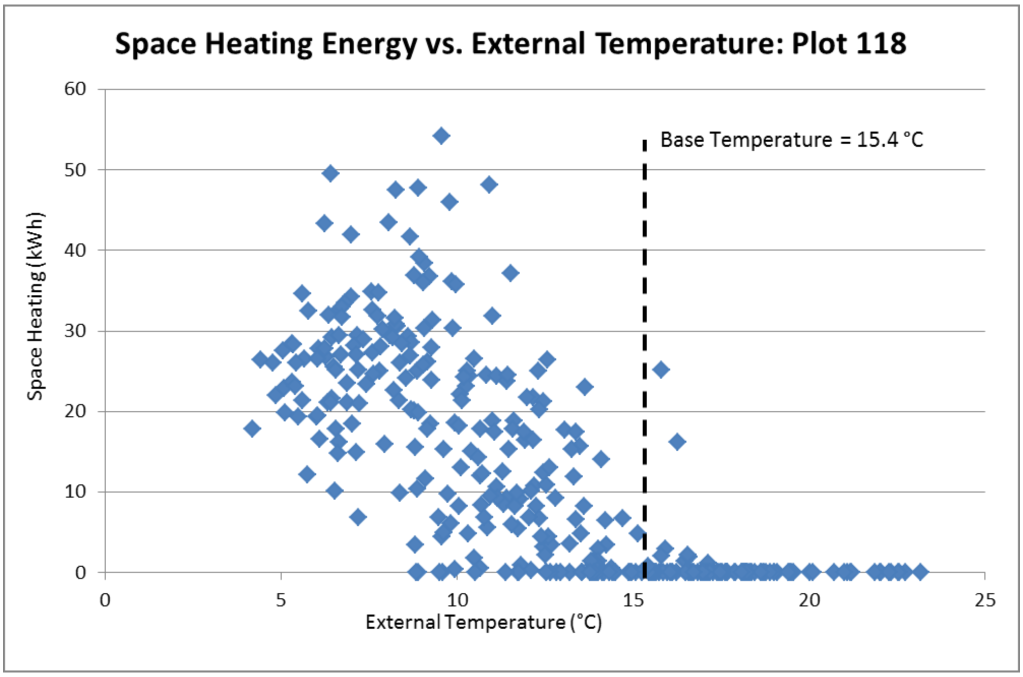


Figure 27 - Daily space heating energy vs. external temperature in Plot 118
1 May 2013 – 30 April 2014

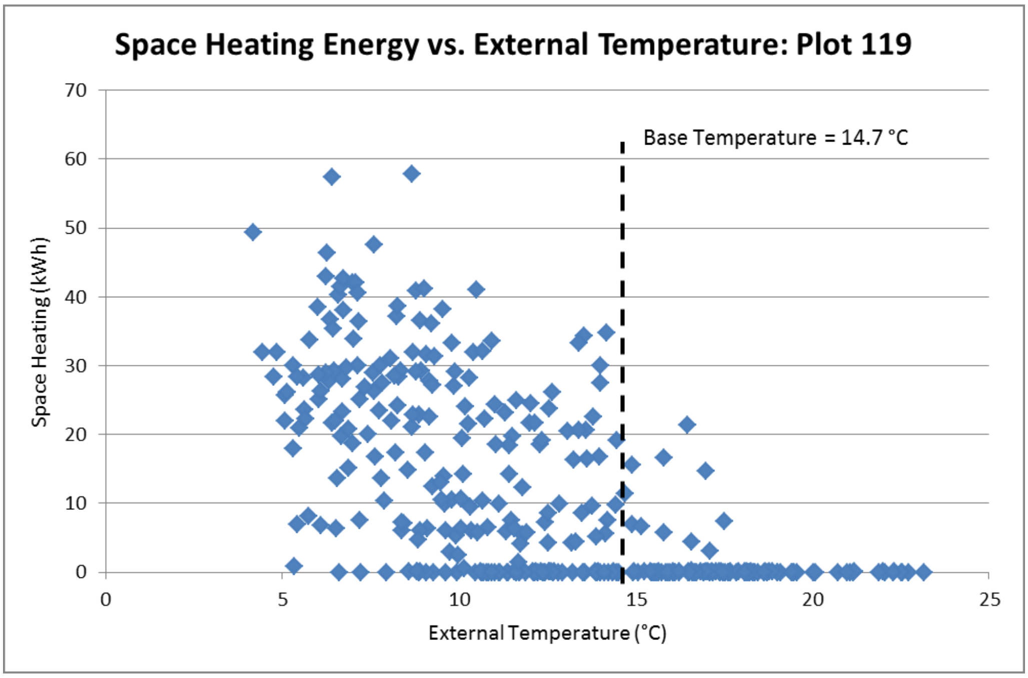


Figure 28 - Daily space heating energy vs. external temperature in Plot 119
1 May 2013 – 30 April 2014

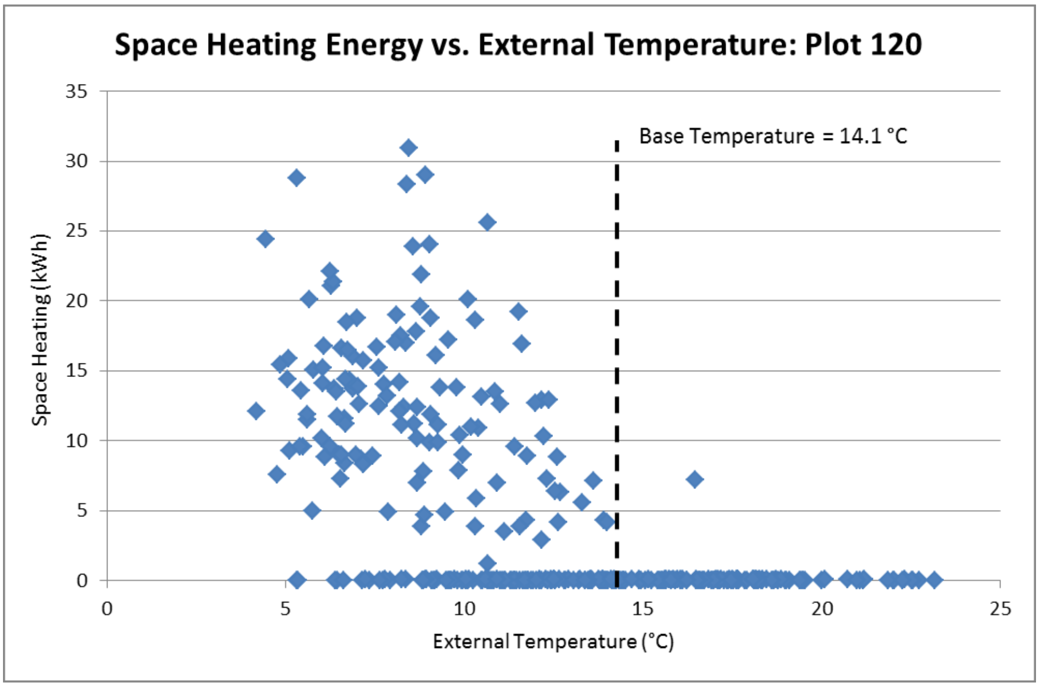


Figure 29 - Daily space heating energy vs. external temperature in Plot 120
1 May 2013 – 30 April 2014

Figure 30-Figure 32 show the correlation between monthly space heating and heating degree days. The graph for Plot 118 shows the highest coefficient of determination which is indicative of good heating control. This is expected as the occupants interview found that the residents of this dwelling allow the heating to be managed by the heating control and thermostats with minimum tampering with the TRVs.

Overall, it appears that occupants in Plots 118 and 119 tend to use higher heating set points that lead to higher space heating energy use, but the operation of the heating system is strongly coupled with the external temperatures. Plot 120, on the other hand, has lower heating set points and energy use with a weaker correlation with external temperatures.

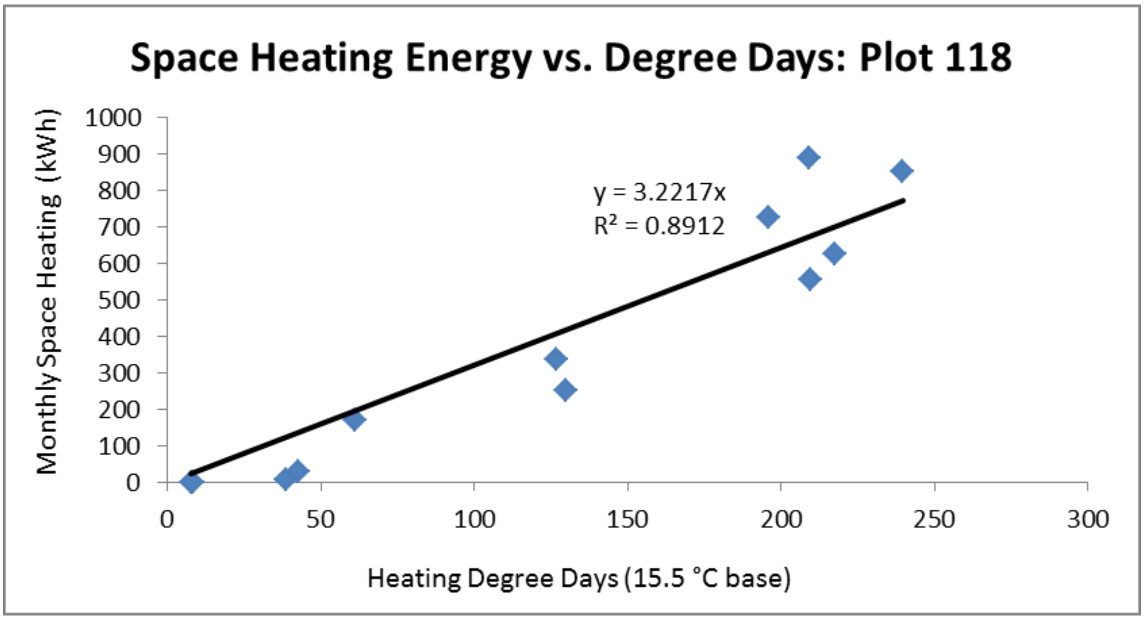


Figure 30 - Space heating vs. heating degree days in Plot 118, 1 May 2013 – 30 April 2014

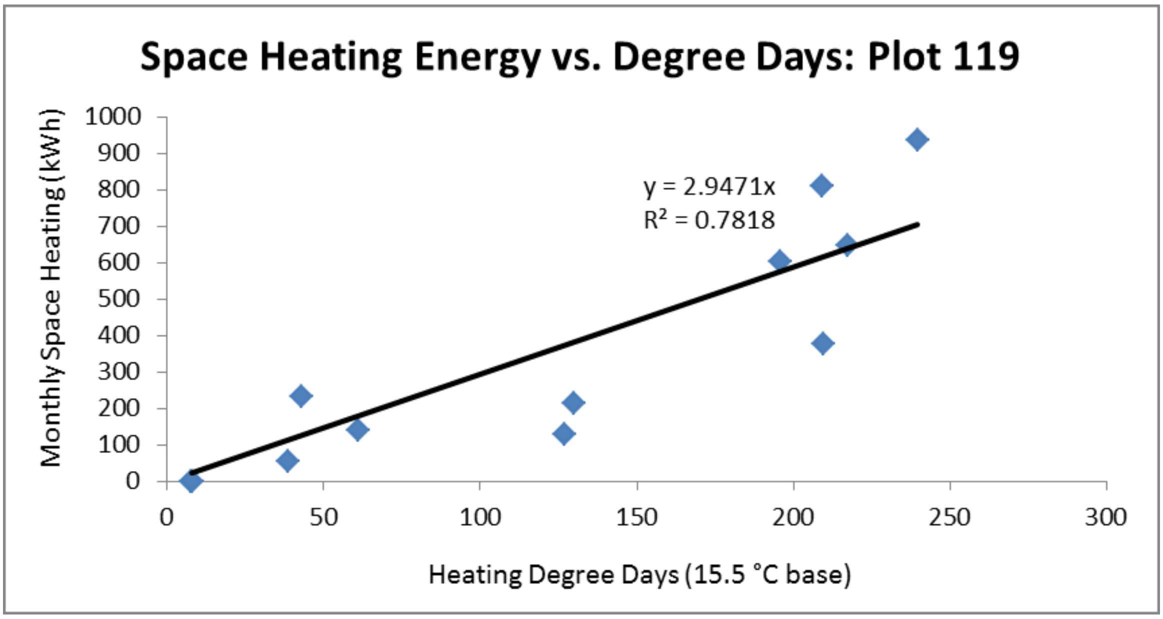


Figure 31 - Space heating vs. heating degree days in Plot 119, 1 May 2013 – 30 April 2014

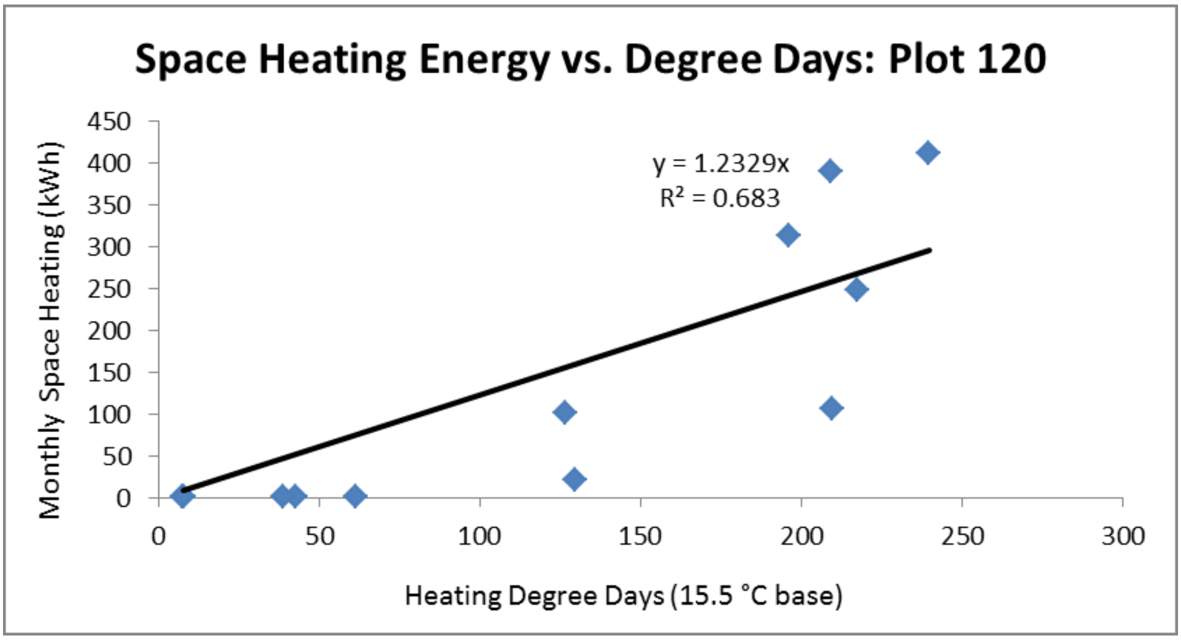


Figure 32 - Space heating vs. heating degree days in Plot 120, 1 May 2013 – 30 April 2014

7.11 Energy performance: domestic hot water energy

As discussed in Section 5, the consumption of domestic hot water was expected to have a significant influence on overall heating consumption in the monitored dwellings, which are well insulated and air tight relative to the existing building stock. The energy demand for Domestic Hot Water (DHW) was calculated on a daily basis from the difference between the data from the ESCO heat meters (total heat input to the dwellings) and the space heating heat meter data. The daily average DHW consumption for the monitored dwellings is summarised in Table 25. The DHW energy use of Plots 118 and 120 is in the expected range, apart from the exceptionally high DHW recorded for Plot 118 in May 2014. However, the DHW energy use in Plot 119 is very high and is equivalent to a hot water use of 300-600 litres (excluding the exceptionally high DHW use recorded in May 2014). This level of DHW use is at the extreme high end of expected use. It is useful to compare this result with the data from EST DHW Field Trial that shows only 5% of dwellings in the 107 dwelling sample had delivered consumption higher than 300 litres [9].

One of the findings of the occupant interviews was that the occupants in Plot 119, on average, tend to take showers twice every day. In contrast, one of the occupants in Plot 118 often takes shower in the work place and the other takes a couple of showers every week. This finding is reinforced by the monitoring data. Figure 33 and Figure 34 show the variation of relative humidity (RH) in Plot 118 bathrooms over a typical week. Figure 35 and Figure 36 show the variation of relative humidity in Plot 119 bathrooms over the same week. RH peaks indicate use of showers/baths. The differences in the number of RH peaks observed in the bathrooms corroborate the differences in DHW energy use reported in Table 25.

Table 25 - Daily mean DHW energy use in the monitored dwellings

Daily Mean DHW use (kWh/day)	Plot 118	Plot 119	Plot 120
Jun-13	-	17.6	3.8
Jul-13	2.6	14.6	2.5
Aug-13	3.1	15.1	2.9
Sep-13	3.2	16.0	2.7
Oct-13	1.4	16.4	3.1
Nov-13	2.9	19.4	4.9
Dec-13	2.3	26.1	4.5
Jan-14	6.5	29.9	7.1
Feb-14	6.4	19.9	6.7
Mar-14	3.4	19.6	5.3
Apr-14	4.6	24.2	2.1
May-14	13.7	50.8	2.0
Jun-14	2.4	17.9	3.8

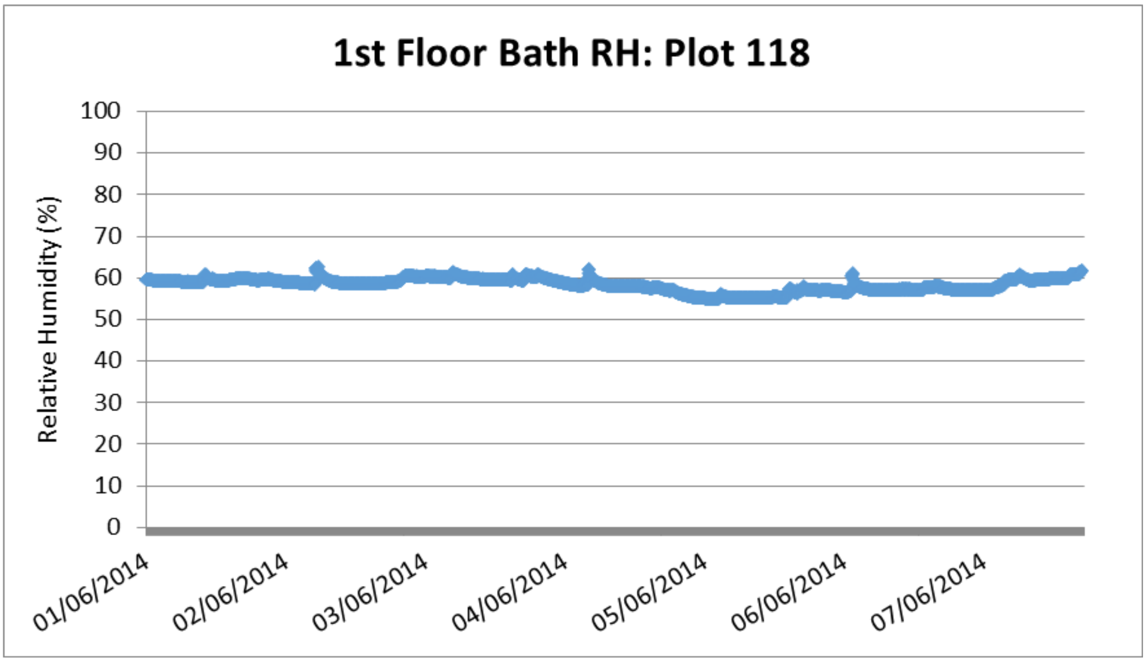


Figure 33 - Variation of relative humidity in 1st floor bathroom: Plot 118

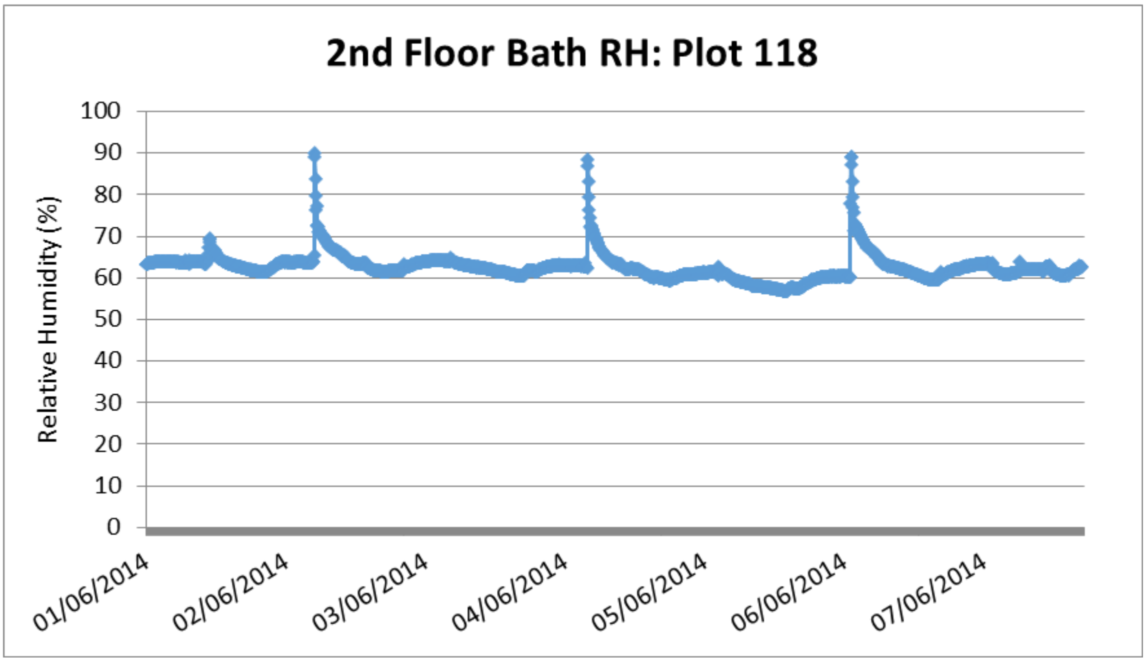


Figure 34 - Variation of relative humidity in 2nd floor bathroom: Plot 118

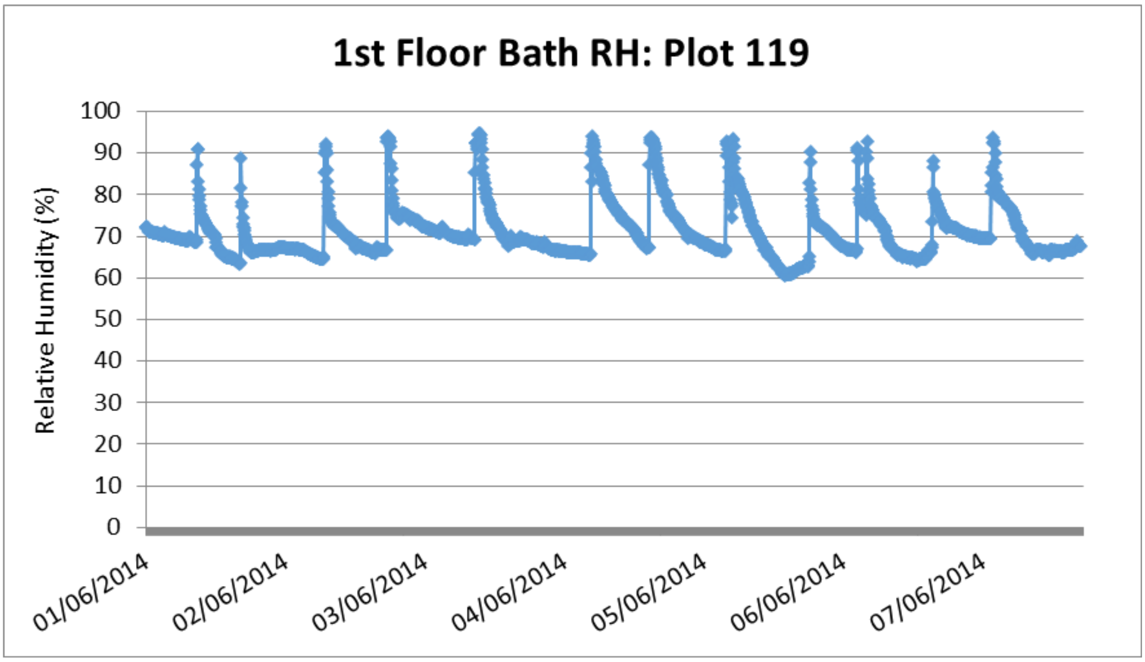


Figure 35 - Variation of relative humidity in 1st floor bathroom: Plot 119

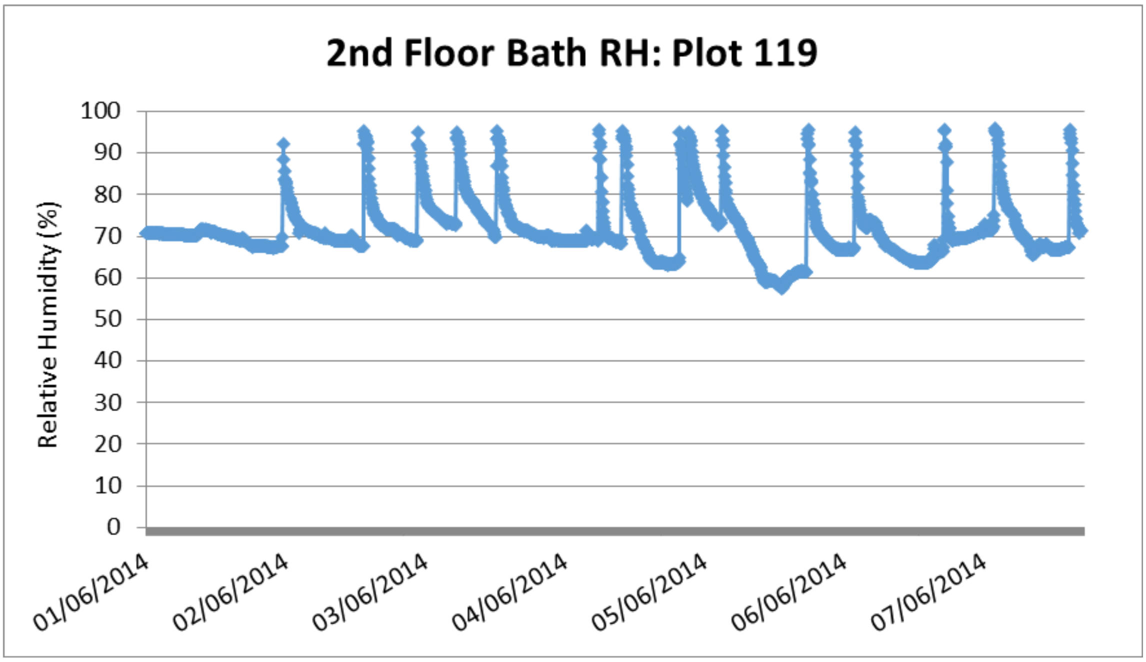


Figure 36 - Variation of relative humidity in 2nd floor bathroom: Plot 119

7.12 Energy performance benchmarking of the monitored dwellings

Figure 37 compares the annual electricity use of the monitored dwellings for the period 1 May 2013 to 30 April 2014 to the benchmarks given for mid-terraced houses in the DOMEARM tool.

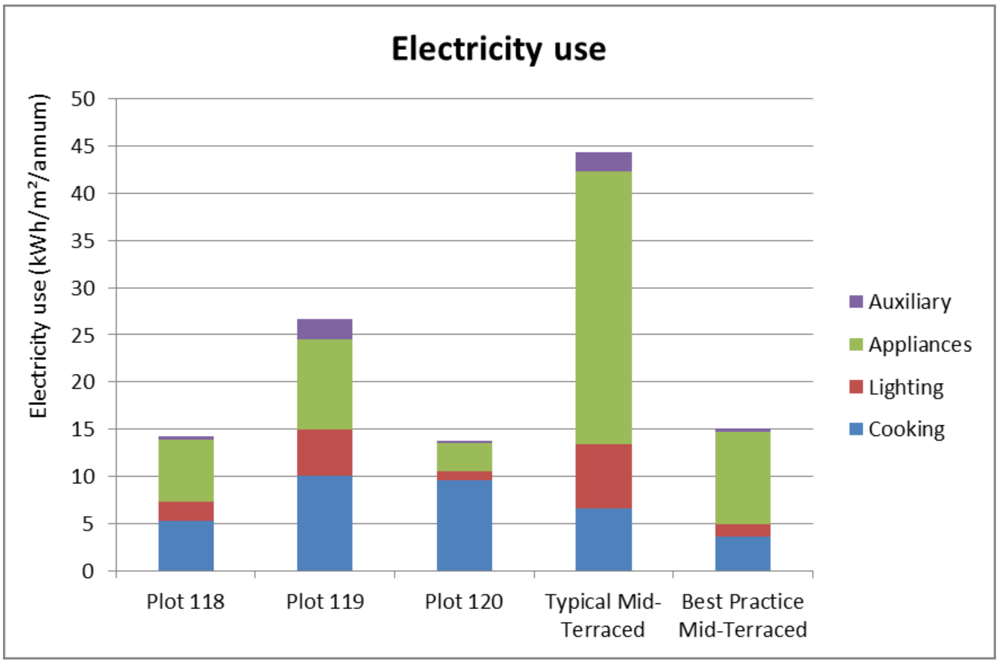


Figure 37 - Electricity use of the monitored dwellings against benchmarks
1 May 2013 - 30 April 2014

Figure 38 compares the thermal performance of the dwellings over the same measurement period with the outcome of the as-built SAP calculations and to the benchmarks derived from existing building stock (mid-terraced houses in the DOMEARM tool).

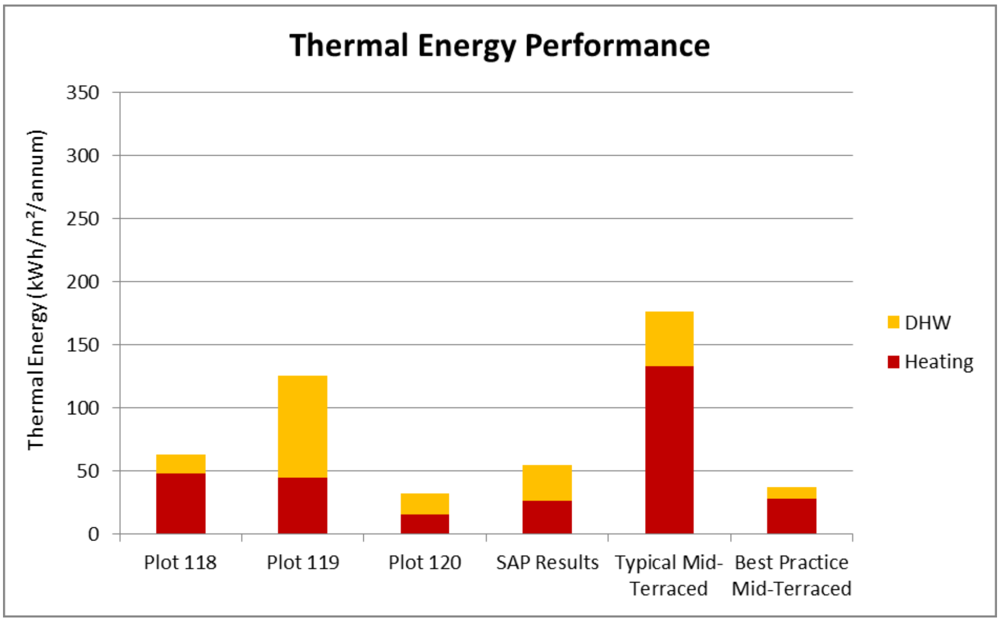


Figure 38 - Thermal performance of the monitored dwellings against benchmarks
(As-built SAP efficiency of the district heating and CHP plant: 87%)
1 May 2013 - 30 April 2014

The efficiency assumed for the district heating system and CHP plant in Figure 38 is identical to the as-built SAP calculations (87%). This is to neutralise the effect of district heating system and CHP plant in benchmarking and give an account of energy efficiency of the individual dwellings. Once the operational efficiency of the district heating system and CHP plant is established, it would be possible to benchmark the total energy performance (see 7.15).

The lighting energy use in Plots 118 and 120 and appliances' electricity use in Plots 118 and 119 are close to the best practice benchmarks. Appliances' electricity use in Plot 120 is actually lower than the best practice benchmark. Electricity use associated with cooking in Plot 118 is close to typical benchmark. However, cooking electricity use in Plots 119 and 120 are higher than both best practice and typical benchmarks. In Figure 37, 'Auxiliary' energy use refers to the electricity use of the MEV fans in Plots 118-120. The benchmarks for 'Auxiliary' energy are derived from existing building stock that usually include house-based gas-fired boiler with associated auxiliary pumping power in addition to any mechanical ventilation that may be present. In this context, MEV fan energy use in Plot 119 seems excessive.

Overall, total electricity use of Plots 118 and 120 is slightly better than the best practice benchmark, while total electricity use of Plot 119 lies between typical and best practice benchmarks. Higher electricity use associated with lighting, appliances and cooking in Plot 119 are, to some extent, expected given the occupancy pattern discussed in Section 5.

Figure 38 shows that thermal performance of Plot 120 over the measurement period was better than the as-built SAP and best practice benchmarks thanks to low heating set points and shorter heating schedules. The thermal performance of the other Plots lies between typical and best practice benchmarks.

One of the findings of the interviews with the occupants was their dissatisfaction with heating bills, especially in Plot 119. Indeed, the total heating energy use in Plot 119 seems high for a new build dwelling. However, during the interview, it appeared that the occupants were more concerned about space heating settings and control rather than DHW use, which is the bigger user of heating energy in this Plot. Better understanding of various energy end-uses and their respective fuel sources could inform the occupants' decision making about appropriate ways to save energy. As explained in Section 5, building occupants were not quite clear about the sources of different energy end-uses. Complexity of the district heating system might have contributed to this issue. It would be useful to give a list of main energy end-uses, the respective fuel sources, and simple ways to save energy in each category in the Home Owners' Guide and during home demonstration in future.

7.13 Performance of the district heating system and CHP plant

A review of the CHP plant and district heating system at Centenary Quay was carried out in September 2013. This analysis highlighted some significant issues with the performance of the system. These issues relate to the overall efficiency of the energy centre, the system power to heat ratio, the efficiency of heat distribution around the district heating network and the carbon intensity of delivered heat. Appendix A includes the detailed analysis and full review of the district heating system and the CHP plant. The theoretical basis for this analysis is in taken from Lowe [10, 11]. The major findings of this study are presented in this section.

7.13.1 CHP engine electrical and heat efficiency

The measured electrical efficiency of the CHP engine over the period October 2012 to July 2013 was 16.8%. This figure has been adjusted to take account of the electrical consumption of the energy centre (~6kW). The CHP engine manufacturer's specification gives an expected electrical efficiency of 30%, so the actual electrical efficiency is around 44% lower than the predicted performance.

The net electrical efficiency of the CHP plant takes into account the difference between the exported and imported electricity to the energy centre, and is given by the equation: (CHP electric export – CHP electric import)/CHP Gas. The measured net electrical efficiency was 13.7%.

The measured heat efficiency of the CHP engine over the period October 2012 to July 2013 was 37.1%. The CHP manufacturer's specification gives an expected heat efficiency of 50%, so the actual heat efficiency is around 26% lower than the predicted performance.

The measured combined net energy efficiency of the CHP engine was therefore 50.8%. This is significantly below the 80% overall CHP efficiency that was used in the as-built SAP calculations for the dwellings at Centenary Quay. The reasons for the discrepancy in performance are unclear, but are likely to be complex and would be related to issues such as the plant size ratio, control strategies, flow temperatures and other operational factors.

7.13.2 CHP power to heat ratio

The measured net power to heat ratio for the CHP plant was only 0.37. This compares to the assumption in SAP which uses a power to heat ratio of 0.60 (this was based on the ratio of the manufacturers quoted electrical and heat efficiencies).

7.13.3 Communal gas boiler efficiency

The overall efficiency of the two communal gas boilers for the period October 2012 to July 2013 was 77.6%. This is below the assumption of 88% used in the as-built SAP calculations. Discussions with the boiler manufacturer (Viessmann) revealed that there are no official manufacturer's efficiency data for the version of boilers installed at Centenary Quay. A verbal "indicative" range of efficiency of 85 to 87% was provided over the phone by a Viessmann technical support engineer.

7.13.4 Overall plant system efficiency

The overall net energy system efficiency of the district heating plant for the period October 2012 to July 2013 was 60.7%. The overall heat efficiency of the district heating plant for the same period was 52.0%.

7.13.5 CHP to gas boiler heat fraction

The overall fraction of heat coming from the CHP engine over the monitoring period October to July was 0.45. This compares to the assumption in SAP of 0.65 (i.e. 65% of annual heat demand coming from the CHP engine). As would be expected, there is some seasonal variation in CHP heat fraction, with the faction of heat from CHP being higher in the summer (around 0.7) when compared to the winter (around 0.4). The effect of a higher fraction of heat from the boiler than predicted tend to increase the overall heat efficiency but would make the system more carbon intensive.

7.13.6 Distribution losses

Distribution losses from the district heating network were calculated using ESCO dwelling heat meter data for the period February 2013 to June 2013, when it is known that all 160 phase 1 dwellings were complete and connected to the district heating network and before any dwellings from phase 2 were connected. The ESCO dataset was incomplete and some adjustments had to be made to allow for occupied dwellings that were missing from the dataset. The overall measured distribution efficiency was 57%. This compares to the assumption in SAP of 95%. The measured efficiency during the heating season (February-March) was 67%, which was higher than that measured during June (40%). This would be expected due to the lower heat demand outside of the heating season. The distribution losses were equivalent to around 69 kW.

7.13.7 Overall system efficiency

The overall system efficiency takes into account all the energy centre efficiencies together with the distribution losses and other system effects. It is given by the equation: (Net electric exported + Heat delivered to dwellings)/ (CHP gas + Boiler gas). The measured overall system efficiency for the 111 day period from 26th February to 17th June was 37%. The overall delivered heat efficiency for the same period was 28%. The overall net power to heat ratio for the energy centre was 0.2 (this takes into account the heat from the CHP and the gas boilers).

7.13.8 Carbon emissions for delivered heat

The observed differences between measured performance of the district heating system and that calculated from the manufacturer's data and SAP assumptions will give rise to a difference in the carbon intensity of heat delivered to the Centenary Quay dwellings. Using the carbon intensity factors from SAP2012 (Grid electricity = 0.522 kgCO2/kWh, Natural gas = 0.212 kgCO2/kWh), the calculated carbon emission factor for delivered heat at Centenary Quay using the design performance data is 0.07 $kgCO2/kWh_{heat}$. However, the actual carbon intensity of delivered heat based on the measured data for phase 1 is much higher at 0.52 $kgCO2/kWh_{heat}$. By comparison, the carbon emission factor for delivered heat from an individual gas boiler (assuming a typical measured boiler system efficiency of 87%) would be 0.24 $kgCO2/kWh_{heat}$. This means, based on current performance, that the carbon emissions for the district heating system are just over twice what could have been achieved using individual gas condensing boilers. The effect of different distribution efficiencies on the measured carbon emission factor are illustrated in Figure 39. It can be seen that even if it is assumed that the communal district heating system has no distribution losses, the carbon emission factor for delivered heat would still be higher than the carbon emission factor for an individual gas condensing boiler.

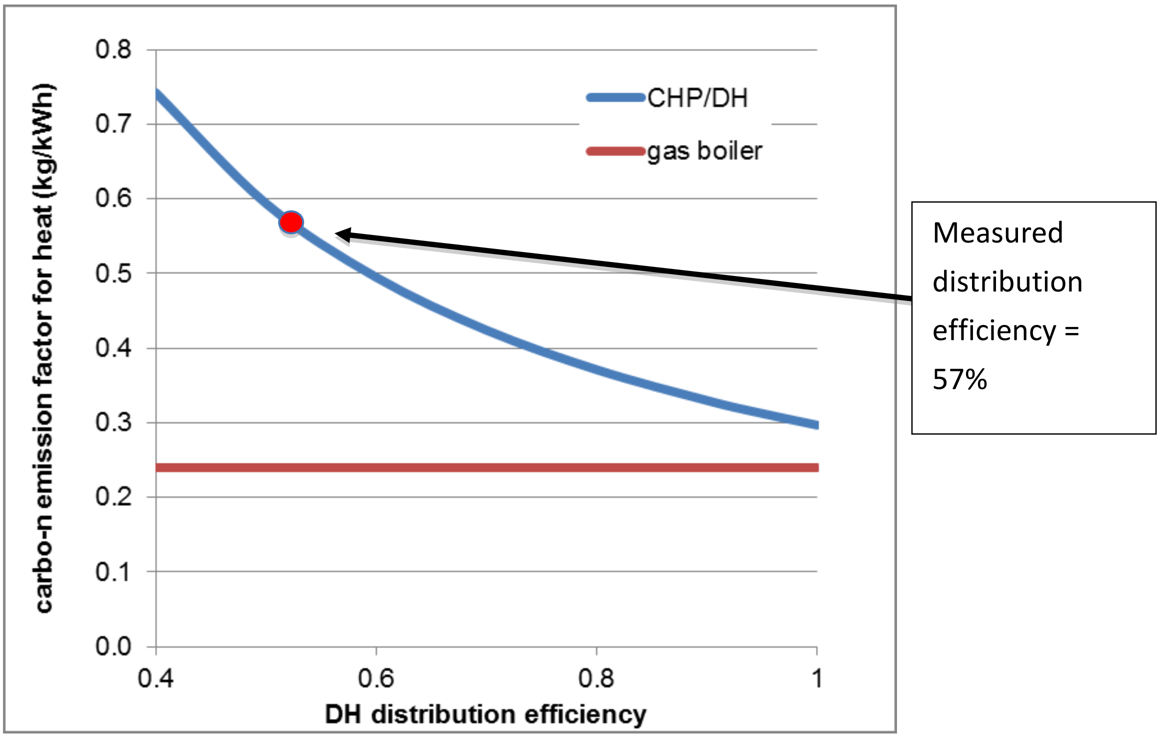


Figure 39 - Carbon emission factors for CHP district heating at varying distribution efficiencies using CQ measured performance data versus individual gas boiler at 87% efficiency

7.14 Benchmarking total energy performance of the monitored dwellings

Assuming the overall system efficiency of 37% established for the district heating system and the CHP plant over the period 26 February to 17 June is representative of the annual performance, it would be possible to benchmark the total thermal performance of the monitored dwellings including the source efficiency. Figure 40 shows how the total thermal performance of the monitored dwellings is compromised by the low operational efficiency of the district heating system and the CHP plant.

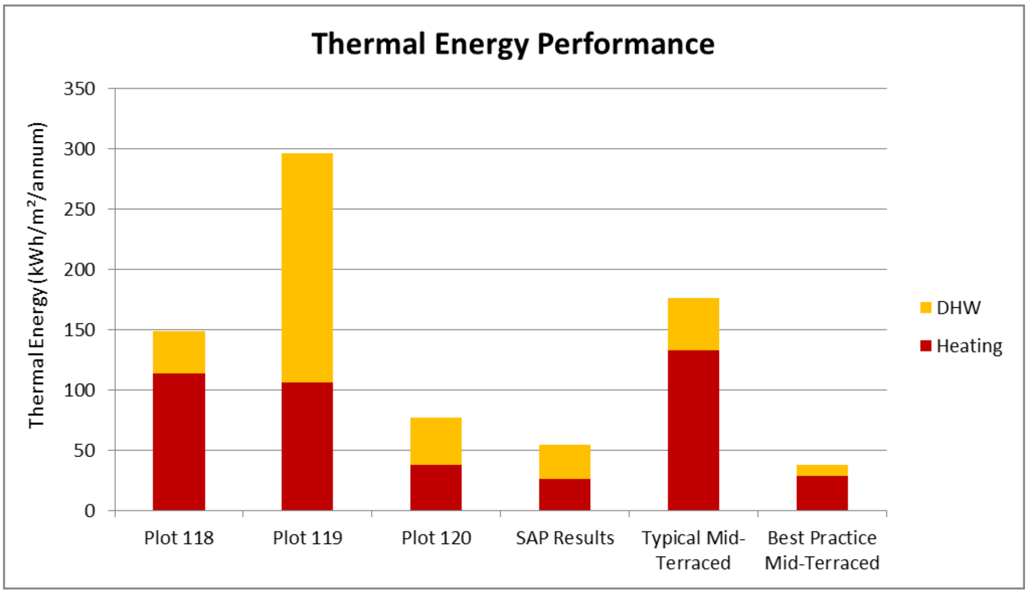


Figure 40 - Thermal performance of the monitored dwellings against benchmarks
(Operational efficiency of the district heating and CHP plant: overall system efficiency of 37%)
1 May 2013 - 30 April 2014

7.15 Conclusions and key findings for this section

The evidence gathered by the monitoring programme, and the review of the operational efficiency of the district heating system and CHP plant point to three major issues that could potentially compromise the operation of the monitored dwellings and occupants' satisfaction:

Overheating:

Analysis of the recorded temperatures over the period 1 May 2013 to 30 April 2014, (in accordance with the overheating criteria provided by CIBSE Guide A) shows that temperatures in bedroom 1, located on the second floor, exceeded the bedroom overheating criterion in all monitored dwellings. Temperatures in the other bedrooms of Plot 118 also exceeded 1% of annual occupied hours.

In the interviews with occupants, one plot felt that their bedroom could be quite warm in summer, though high summertime temperatures were not flagged as a major issue in the interviews. The interviews also revealed a clear gender difference in perceived thermal comfort. This is not taken into account in any overheating protocols currently used in the industry.

The BUS survey results showed a high proportion of respondents perceived the dwellings to be too hot in summer. 62% of the BUS survey respondents lived in houses and 38% lived in apartments.

With these results, it is worth emphasising that overheating could become a major issue in the future if, as expected, summertime temperatures increase over the coming years.

It would be difficult to identify the exact root causes for overheating in the monitored dwellings. Internal heat gains and the way occupants operate the windows will play an important role. However, from a design point of view, there are effective ways to reduce the risk of overheating including using thermal mass, increasing the window operable area, high performance glazing, etc. In the context of the monitored dwellings, it is notable that the Dwelling Emissions Rate reported in the as-built SAP 2005 calculations was significantly lower than the Target Emissions Rate to the extent that the dwellings could have complied with the more stringent energy performance requirements of SAP 2009. It is not clear whether a trade-off between energy performance targets and thermal comfort was considered at design stages to increase the operable areas or the project was perhaps too focused on various energy performance targets that went beyond regulatory requirements. In any case, such a trade-off seems reasonable especially in the context of the future climate change and the prospect of higher ambient temperatures. UCL pressure tests on Plot 120 suggest that air permeability of the monitored dwellings is higher than regulatory pressure tests and the design target of 6 $m^3/h.m^2$ @ 50 Pa. If the air permeability of the external envelope was as low as the design target, the overheating risk could be potentially even higher. This is another example of the conflict between energy performance requirements and thermal comfort. Finally, as discussed in the final report for Phase 1, one possible practical solution for reducing the risk of overheating in the monitored dwellings would be to turn off the "keep-hot" facility in the HIUs or provide additional insulation on pipework.

Underperformance of the MEV system:

Two different methods were used to assess the extract flow rates of the MEV system: spot check with vane anemometer and flow capture hood, and long-term measurements with velocity probe. Both methods show the MEV flow rates are generally lower than design specifications (the only exceptions being the flow rates inferred from the ductwork velocity readings in Plot 119 kitchen and WC). Other physical measurements that may point to shortcomings in the ventilation performance are steady increases in CO_2 concentration levels, and the long time-downs associated with bathrooms' peak relative humidity. While under-ventilation could contribute to overheating problem discussed above, it can also lead to condensation issues, mould growth and health problems. A number of issues related to the installation and commissioning of the MEV system were uncovered in Phase 1. The implication was that the commissioning process used for the MEV system was not robust. There are also likely to be underlying problems with MEV installations such as flow restrictions and duct leakage. It is notable that the MEV fan energy use in Plot 119 is significantly higher than what the specific fan power quoted by the manufacture suggests; the implication being the system pressure loss and actual specific fan power are much higher than expected. It is expected that changes to the commissioning process introduced in Part F 2010 will begin to address some of the issues associated with the installation and commissioning of the MEV systems.

Crest Nicholson has put in place several measures to respond to the issues highlighted in Phase I and II of this project relating to the underperformance of the MEV system. Please refer to sections 4.2 and 7.9 for explanation of these.

Operational efficiency of the district heating system and CHP plant:

The key message of the study carried out by UCL on the performance of the district heating system and CHP plant was that there are serious shortcomings in energy centre efficiency, system power to heat ratio and heat distribution efficiency. Figure 40 shows how the lower than expected operational efficiency of the district heating system and the CHP plant can compromise energy performance of the monitored dwellings. The carbon intensity of the district heating system, at the time of the review, was almost twice that of individual condensing gas boiler. These results would make it easy to conclude that it's better to use conventional gas boiler systems in future rather than district heating and CHP. However, the district heating system and CHP plant provide ample opportunities for decarbonisation in the long term, such as utility scale heat pumps, hydrogen fuel cells, large scale solar and biomass. The measured performance of the existing system in Centenary Quay is not indicative of its long term prospect. In fact, since UCL team completed their review, the following improvements have already been made to enhance the operational performance of the system:

- An improvement to the control system logic to ensure the CHP engine operates at an optimum heat and electrical output.
- An improvement to the system to ensure heat is delivered from the energy centre and not lost within the energy centre due to mixing in the thermal store.
- Adjustment of district heating flow and return temperatures to reduce distribution losses.
- Identification and replacement of possible areas of missing or defective insulation to pipework.
- Improvements in metering to ensure accuracy, including the addition of further heat meters to better understand network behaviour.

8 Key messages for the client, owner and occupier

Technology Strategy Board guidance on section requirements:	This section should investigate the main findings and draw out the key messages for communication to the client / developer and the building owner / occupier. Drawing from the findings of the rest of the report, specifically required are: a summary of points raised in discussion with team members; recommendations for improving pre and post-handover processes; a summary of lessons learned: things to do, things to avoid, and things requiring further attention/study. Try to use layman's terms where possible so that the messages are understood correctly and so are more likely to be acted upon.

8.1 Overheating

When measured against CIBSE Guide A, measurements showed that overheating in the bedrooms of the monitored dwellings at Centenary Quay could be a serious risk. The BUS survey carried out in Phase 1 also showed that a high proportion of residents said the dwellings are too hot in summer. The survey included 24 responses, with 62% being from respondents living in houses. The summer temperature score placed the dwellings included in the BUS survey in the 30th percentile of the database (Figure 41). Summer temperature was among the lowest scores achieved in the BUS survey. However, it should be noted that the customer feedback received from the occupants in the monitored dwellings does not suggest that overheating is a serious issue at present.

The exact causes of the overheating in the monitored dwellings are not fully understood. Overheating could be, to some extent, related to occupants' behaviour (e.g. window opening, incidental gains from appliances and use of curtains and internal blinds). The issues related to the installation and commissioning of the MEV systems could have also reduced the potential of the ventilation system to minimise overheating risk. Furthermore, the heat gains arising from losses from the communal heating system pipe work and the keep-hot facility in the HIUs could contribute to overheating.

The monitored dwellings at Centenary Quay would be at risk of serious overheating when subject to high external temperatures expected as a result of climate change over the coming years. It is recommended that building occupants are provided with advice on simple measures that could be implemented to reduce overheating potential. Technical solutions to address the problem might range from reducing the district heating flow temperature or turning off the communal heating when external temperatures are high, to the installation of shading or external blind.

It is recommended that information about mitigating the risk of overheating are provided in the home user guide and covered during home demonstration in the future. This is particularly important as the risk of high ambient temperatures is increasing with climate change.

It is also important to carry out robust overheating assessment at the design stages taking into account the future climate, and the possible trade-offs between energy performance and thermal comfort.

Finally, with the ever-increasing tendency toward air tight buildings in pursuit of energy efficiency, installation, commissioning and communicating the mechanical ventilation systems, including MEV systems, is highly important and must be properly addressed throughout the design stages & building procurement.

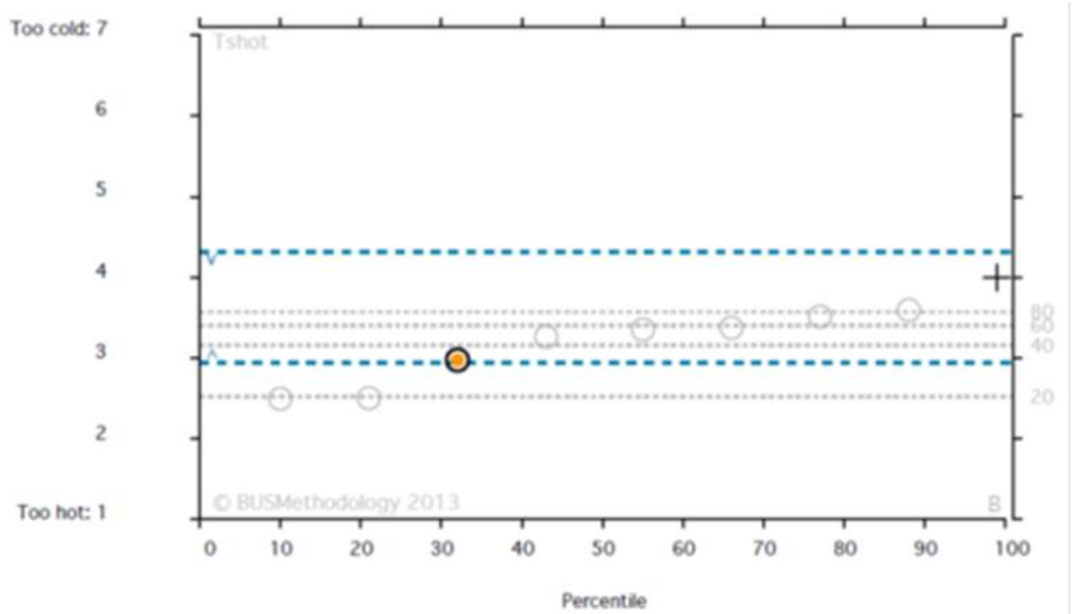


Figure 41 - Graph of BUS response for summer temperature hot/cold

The issue of overheating is one which is faced by the entire new build housing sector as requirements for increased thermal performance of homes must be balanced against the need to build homes that can adequately respond to the anticipated possible effects of climate variation and extreme weather conditions. Finding this balance is further challenged by the current inadequacy of tools and data available to developers and design teams for estimating and designing to manage overheating potential.

Within the body of this report, Crest Nicholson has outlined its response to the issues identified relating to overheating within dwellings. This has included putting in place robust systems to analyse overheating potential and mitigate for this. Please refer to section 7.8 for further details of Crest Nicholson work in this area.

8.2 MEV system performance

The post construction and early occupation study carried out in Phase 1 identified a number of issues related to the installation and commissioning of the continuous Mechanical Extract Ventilation systems specified for the monitored dwellings. Excessive use of flexible ducts, tight bends, lack of over-run function and humidistat control in wet rooms, and restricted ridge terminals were among the technical issues. Furthermore, no commissioning certificate or any other test data was made available to the project team. While there was no requirement to provide commissioning certificates for mechanical ventilation system under Part F 2006, as the performance inputs for the MEV system installed were taken from the SAP Appendix Q database, there was a requirement to provide Appendix Q MEV commissioning checklists to SAP assessor and the building control officer. The research team are not aware of any such checklist completed for the monitored dwellings.

With this background and given the difficulties the construction sector has in achieving the expected performance in mechanical ventilation systems, it is perhaps not surprising to see underperformance in the installed MEV systems in all monitored dwellings. These shortcomings can contribute to the potential overheating problem and could also lead to condensation, mould growth and health issues.

While the requirement of providing mechanical ventilation system commissioning certificates, introduced in Part F 2010, could help improve the commissioning process, it is also vitally important to balance the need for sufficient air exchange to maintain good indoor air quality with the requirement to minimise air leakage at design stages and building procurement.

Please see sections 4.2 and 7.9 for more information about how Crest Nicholson has responded to the issues relating to underperforming MEV systems.

8.3 Base temperature of new build dwellings

Base temperature is the threshold mean external temperature for operation of heating system in a dwelling. The minimum empirical base temperature established for the monitored dwellings, based on recorded external temperatures and space heating energy data, was 14.1 °C. This is significantly higher than the theoretical base temperature of 10.9 °C calculated in the as-built SAP assessments. Part of this difference could be explained by the differences in operating conditions (e.g. higher heating set points in Plot 118 than the SAP assumption of 18.3 °C, variations in internal heat gains, etc.). However, the fact that all monitored dwellings have higher base temperatures, despite major differences in occupant behaviour, points to fabric underperformance being an important factor. Examples of shortcomings in fabric U-values and air tightness were provided in the final report for Phase 1 of the project. Addressing the underlying causes of these issues is critical for the construction industry to achieve a performance level close to what is expected from new build dwellings.

8.4 District heating system and CHP plant

Despite the disappointing outcomes of the initial assessment on the performance of the district heating system and CHP plant installed for Centenary Quay development, it should be noted that this system has huge potential for improvement and is capable of reducing the development's CO_2 emissions substantially subject to some improvements. One of the key lessons learned here is that it is vital to choose an experienced contractor to deliver the district heating system who can take responsibility for the design, installation, commissioning and management of the system. E.ON, the existing operator of the system, inherited a CHP scheme not originally designed by them and had limited flexibility to change key aspects of the specification such as pipe-work, HIU units and main plant. It should also be noted that this was the first time the project team had delivered a CHP based district heating system at this scale.

8.5 Benchmarking measured performance

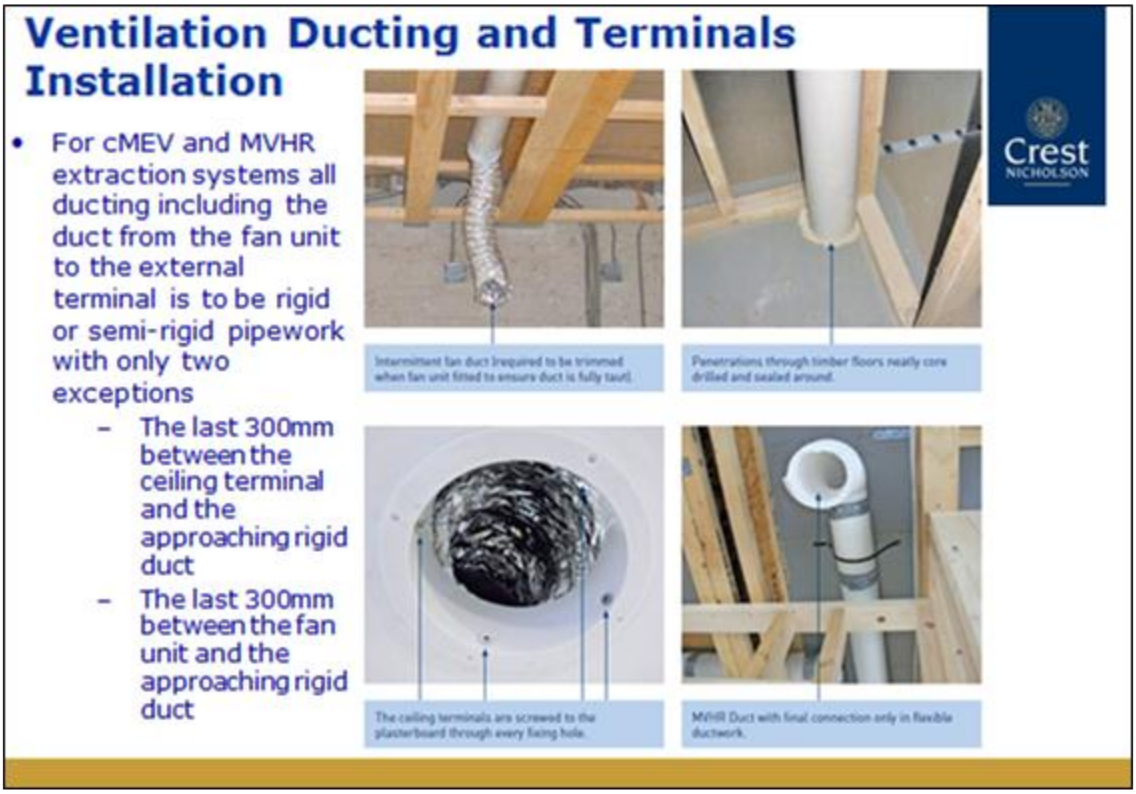
Overall, the monitored dwellings in Centenary Quay compare favourably with the energy benchmarks when the effect of the district heating system and CHP plant is neutralised. Total electricity use of Plots 118 and 120 is better than DOMEARM best practice benchmark for mid-terraced houses. Plot 120 heating performance is also better than best practice benchmark when identical heating efficiencies or delivered heat are used for benchmarking. There are lessons to be learned for the future projects; for example in calculating and accounting for thermal bridges more accurately, procurement of the MEV or other mechanical ventilation systems, trade-offs between air-leakage and indoor air quality, and overheating prevention. However, the outcome of the BUS surveys, interviews with the occupants and energy performance analysis at building level show some positive aspects of the in-use performance. At this stage, the priority for energy performance and carbon emissions at Centenary Quay is to improve the performance for the district heating system and CHP plant.

8.6 Other lessons learned by the developer

Throughout this report, Crest Nicholson has outlined how it has responded to the specific design, commission, build, and internal environment issues highlighted during this Building Performance Evaluation research project. Please refer to sections 4.2, 7.8, and 7.9 for these. However, there are two wider lessons that Crest Nicholson have taken from participating in this and other post-occupancy research, as well as from the Group Technical & Quality Director's secondment to the Zero Carbon Hub, which have culminated in new processes and improvement initiatives.

The first is the renewed investment and revised process around build quality, which has resulted in a Quality Manual and Build Stage Inspection Sign Off procedure as well as new roles within the Group Technical & Quality team to fully support driving our quality agenda. The aim of these documents and processes is to set benchmark standards for site teams' inspections, support Commercial and Build teams in assessing whether work meets the standards set by Crest Nicholson, and provide clear guidelines to subcontractors working on site.

One particular example that resulted from participating in the TSB Building Performance Evaluation was around duct work and the installed MEV system, which was discussed in the Phase I final report. Below is a summarised extract from a presentation on the Quality Manual, which discusses ventilation ducting.



Other examples include bespoke training for site managers on ventilation and a new commissioning guide for mechanical and electrical systems.

The second is around organisational learning and how to usefully embed both the detailed and wider lessons and insights that participating in post-occupancy research produces. There is recognition that strong learning and feedback loops are needed within the business and with its supply chain partners. As a result of this, Crest Nicholson is undertaking a wider programme of work to embed learning and feedback loops within the business through its Organisational Learning work stream, one of five key work streams within the ten-year Sustainable Business Strategy. Key members of the team that oversaw this Building Performance Evaluation project are members of the working group to ensure that their experiences are built upon.

9 Wider Lessons

Technology Strategy Board guidance on section requirements:	This section should summarise the wider lessons for the industry, including, but not limited to clients, other developers, funders, insurance bodies, skills and training groups, construction team, designers and supply chain members to improve their future approaches to this kind of development. Provide a detailed insight in to the emerging lessons. What would you definitely do, not do, or do differently on a similar project. Include consideration of costs (what might you leave out and how would you make things cheaper); improvement of the design process (better informed design decisions, more professional input, etc.) and improvements of the construction process (reduce timescale, smooth operation, etc.). What lessons have been learned that will benefit the participants' businesses in terms of innovation, efficiency or increased opportunities? These lessons need to be disseminated through trade bodies, professional Institutions, representation on standards bodies, best practice clubs etc. Please detail how dissemination will be carried out for this project. As far as possible these lessons should be put in layman's terms to ensure effective communication with a broad industry audience.

9.1 SAP calculations & Building Regulations compliance

The evidence from Centenary Quay is that there can be several errors in SAP inputs, inaccuracies in U-value calculations and a failure to check builder submissions for the appropriate commissioning documents and test certificates. This is perhaps not surprising. In previous research carried out by the Energy Efficiency Partnership for Homes that looked at a sample of 82 SAP assessments, all had some level of error, and in 20% of cases these errors would have resulted in the assessment failing to meet the dwelling target emissions [12]. However, in case of the monitored dwellings at Centenary Quay none of the errors and inaccuracies was large enough to have caused the SAP assessments to fail had they been corrected.

In a broader context, a study on 404 new-build dwellings in England and Wales revealed that only a third of these buildings were compliant with the energy efficiency requirements set out in the Building Regulations. This study points to the lack of adequate knowledge about energy efficiency requirements of the Building Regulations among the supply and building control side of the construction sector [13].The pace of change to building energy regulations also contributes to this inadequate knowledge of the energy efficiency requirements. As for SAP calculations, there are clearly opportunities to improve the SAP assessment process and associated training, information and support for SAP assessors, Building Control Bodies, designers and housing developers. Problems around SAP are, to a large extent, systemic and not the sole responsibility of house builders. But the fact that they have emerged and have been documented in this project provides the project team with an opportunity to raise them with all relevant stakeholders.

9.2 Overheating analysis: from regulatory assessment to good practice design

The risk of overheating is likely to increase in the future with the rises in seasonal atmospheric temperature that may result from climate change. Comparing the outcomes of SAP overheating analysis with that of CIBSE Guide A showed that CIBSE Guide A requirements are more stringent. The method proposed by CIBSE Guide A is more robust as it relies on annual temperatures as opposed to mean summertime temperature used in the SAP procedure. It also provides different overheating thresholds for bedrooms and other living areas, whereas the SAP procedure is dependent on mean internal temperature thresholds that are defined for the whole dwelling. While the monitored dwellings at Centenary Quay did not show a high risk of overheating using the SAP procedure, it is recommended that for the future projects the overheating criteria set out in CIBSE Guide A and the Design Summer Year (DSY) weather conditions are used to give better indication of the overheating risk at design stages. Design for the future climate that takes into account the projected weather conditions for the future climate based on different greenhouse gas emissions' scenarios would be the next step to ensure the buildings are resilient to climate change. See Crest Nicholson response in section 7.8.

9.3 Community heating operational performance

The findings of this study related to the district heating system and the CHP plant is another evidence of underperformance in community heating schemes that, if not addressed, could seriously compromise the CO_2 emissions targets set out by the UK Government in the construction sector. Another TSB project completed by UCL also showed that the actual carbon emissions for the delivered communal heat was ten times higher than predicted, and twice that which would have been expected had the development used individual gas-fired boilers for heating [14]. There is a tendency to specify district heating for large new housing developments due to the huge potential of these schemes for carbon abatement. However, it is vitally important to have a better understanding of the risks associated with these schemes and improve their operational performance to achieve the carbon emissions saving targets in practice. A requirement for ESCOs to publish operational data could be a good incentive to improve performance and also provide data for further research about the effectiveness of these schemes in the future.

9.4 Building Performance Evaluation methodology

The Building Performance Evaluation (BPE) project at Centenary Quay development included measurements of the post-construction performance and post-occupancy evaluations. While the feedback received from the design team and M&E subcontractor helped the research team link some of the findings of the post-construction studies to the decisions made during the design stages, a better understanding of the underlying process issues would require a model for building performance evaluation that is fully integrated into the design and construction process. This would make it possible to relate the measured performance data to building procurement, design and construction processes. The Soft Landings framework, which aims to integrate the Soft Landings process into the RIBA plan of work from the outset of a project, could be used as a model for future performance evaluations to provide deeper insights about the underlying causes of performance and ways to improve building procurement processes [15].

10 References

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