Edinburgh Napier UNIVERSITY

Institute for Sustainable Construction

Construction technologies for tomorrow's communities

Energy Performance of homes using Modern Methods of Construction

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Led by Prof John Currie, the **Scottish Energy Centre (SEC) as part of the Institute for Sustainable Construction at Edinburgh Napier University** has a pre-eminent record in the development of renewable energy systems and sustainable design in construction. Founded in 1984 as a portal for research, knowledge transfer and expert services activity in the energy sector the portfolio of activities have expanded to help support commerce and industry in meeting the challenges of recent energy price increases and government initiatives and statutory requirements. The SEC has a unique position in the market for provision of commercial technical support services; with specific strengths in the field of energy diagnostics, modelling, and integration of low carbon technologies.

Professor **John Currie** is Director of the Scottish Energy Centre at Edinburgh Napier University and Fellow and Chairman of the Energy Institute in Scotland. A Chartered Engineer with over 30 years' experience in teaching, research and practice John was formerly Chief Engineer with Carlsberg Tetley Brewing. Widely published, his research interests currently include improving building energy & environmental performance, monitoring and modelling pollution in the urban environment, and the development of novel low carbon technologies. He presently Co-Chairs the Scotland 2020 Climate Group, recently launching 'Retrofit Scotland', and sits on the Engineering Accreditation Board of the Engineering Council.

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Jon Stinson graduated from Edinburgh Napier University in 2007 with an honours degree in Architectural Technology. He joined Scottish Energy Centre at Edinburgh Napier University as a research assistant after completing a research degree in low carbon strategies and SMART technology. During this time he was involved with monitoring the impact of energy awareness technology on the social and behavioural aspects of domestic energy use, addressing fuel poverty and the carbon reduction agenda. Jon currently works in the field of thermal performance of historic buildings and performance evaluation of newly built low and zero carbon homes.

EXECUTIVE SUMMARY

The Housing Innovation Showcase (HIS), developed by Kingdom Housing Association (KHA) comprised of twenty seven dwellings of varying size and form, using ten different Modern Methods of Construction (MMC) techniques; twelve flats with communal gardens, and eleven terraced houses and four bungalows, all with private gardens.

The evaluation of the HIS properties was split into two phases comprising two distinct parts; the first phase, part one, formed a pre- and post-handover early occupation Building Performance Evaluation (Jack, Currie, Bros-Williamson, et al. 2013).This report, which forms the second part of phase 1, focuses on an initial 12 months of occupation following handover, comparing actual energy consumption against predicted energy consumption This analysis was performed by logging consumption data using an In-home Energy Display Monitor (IEDM) correlated by meter readings; which permitted a direct comparison with predicted consumption.

The report analyses energy use derived from a combination of heat and electricity consumption and comparing it with typical household figures and average regional figures whilst observing total carbon and cost comparisons across the development.

Despite the best efforts from KHA and stakeholders in designing and building quality homes to meet specific targets, the results of energy for space and water heating consumption were substantially higher than the predicted. This gap in performance ranged from properties being 5% to 350% higher than design values. This gap in energy consumption also produced disparities in total dwelling heating costs with a £175 increase between the mean predicted and the mean delivered. In comparison, the HIS development was £254 below the typical Scottish mean expenditure (£537/yr).

This performance gap is a result of: construction type discrepancies, for example some ground floor concrete slabs not being level creating problems in the timber frame erection, varying occupant comfort and behaviour patterns; creating different heating patterns thus consuming unusual amounts of energy, and the result of using different building services where controls weren't adequately operated, deemed to be complicated or not operating as expected.

The study will continue into the next monitoring phase; focussing on testing a smaller representative sample of dwellings which includes a long term analysis of energy consumption, re-evaluating the properties thermal envelope and monitoring the correlation between indoor air quality (IAQ) and dwelling ventilation systems. It is hoped that such results can deliver a greater understanding of environmental performance; going beyond the work of most other studies to-date.

Figure 1: Design stage 3D render of the HIS site. Source: Oliver Robb Architects 2012.

INTRODUCTION

Phase one, part one of this study analysed the impact that the building envelope, services, and residents had on the dwellings energy performance at an early stage of occupancy. This second part of the study focuses on analysing energy consumption over a full year of occupation, together with any energy inputs generated by low carbon technologies installed in the dwelling. The aim was to compare actual energy consumption figures against those predicted from calculations during the design stage where the Standard Assessment Procedure (SAP) was used.

There is little published work on the subject of household energy consumption following a Post Occupancy Evaluation (POE) when compared to other building types, e.g. offices, commercial and industrial properties (Stevenson & Leaman 2010). This study seeks to explore energy consumption of 3 different dwelling types (flats, bungalows and terraced homes) across the 10 blocks and system providers, amounting to 25 homes in total.

One of the main objectives of this study is to create a profile of energy consumption and production that will correspond to the occupancy and dwelling type under the benefits and constrains that the method of construction delivers. This information will present an interesting dialogue between architects and system providers on how predicted energy differs from actual energy usage and provide evidence to regulatory authorities on the shortcomings and strengths of some of the implemented Modern Methods of Construction (MMC), together with the effect on carbon reduction targets.

Although difficult to separate, occupancy patterns of use are naturally embedded into the energy consumption totals and are analysed concurrently with the numbers of occupants, hours of use and weekly activities.

BACKGROUND

This report follows the Phase one part one study that was conducted during the pre and post-handover stages covering an early occupation period. The first document reported on the evaluation of the dwelling envelope and servicing technology following the construction phase and during the early stages of occupation. Results from building heat loss (In-situ U-value), air tightness and infra-red thermographic surveys concluded that there were differences between the as-designed and the as-built figures, creating a post construction gap in performance. Both the envelope and services gap in performance results were presented as early occupation figures.

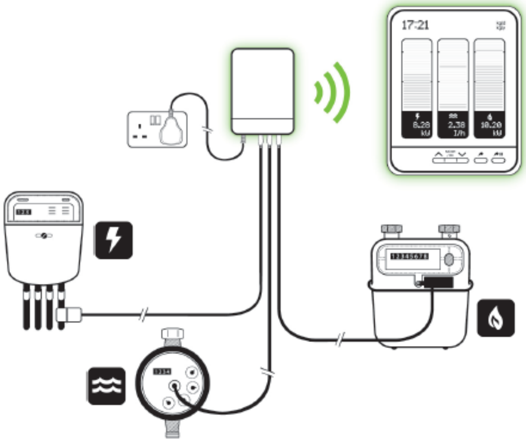
The Phase one part one BPE document analysed monthly early occupation energy consumption figures following hand-over. These figures were compared with equivalent SAP derived figures but were deemed to hide the real energy performance gap as the period included the non-heating months of the year. Full year energy figures will thus provide a more representative analysis of the dwellings energy performance.

In-House Energy Display Monitor (IEDM)

An IEDM was fitted into each property providing a direct feedback to the dwelling occupants of real-time energy use. This embedded technology allowed the BPE Study Team to download hourly energy consumption data which could later be analysed to provide daily, weekly, monthly and yearly energy demand profiles. This information was validated and verified against utility meter readings. All IEDM devices installed in the properties had the capability to log three separate consumption channels. All devices were thus configured to log total electricity and gas consumption allowing the third channel to log, for instance, electricity produced from a Solar PV array. Separate heat metering was used to log solar thermal and air source heat pump (ASHP) delivered energy. A list of all the data logging channels and inputs is listed in Appendix A of this document.

The IEDM device connected via a pulse output to the electricity meter or by using a current transformer where a meter output was unavailable. Gas consumption was monitored via a pulse block installed on the meter (EWGECO 2011). These were later connected to a transmitter which connected wirelessly via Zigbee 2.4GHz communication to a traffic light display unit revealing energy consumption in kW, £ per kW or kg of CO_2.

Some properties were able to connect their transmitters to a wireless internet device that can store and display their consumption in a web portal service called “My EWGECO”. This facility was useful as it avoided downloading the stored data in the display device manually by computer, which required occupant access and availability. Only 11 of the 27 homes had this device and system installed.



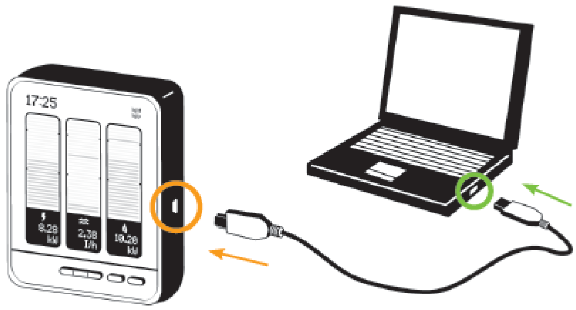


Figure 2: (left) Connection diagrams for Electricity, Gas and water pulse/ CT outputs. Source: (EWGECO 2011)

Figure 3: (right) Download capabilities via physical download

Demographic study & sample size

An attempt was made to collect data from all 27 dwellings as part of this study. Whilst some residents were available at all times, others were difficult to contact or were simply not interested in taking part in the study. The success rate of data retrieval was considered to be positive with questionnaires and full 12 month data retrieved from 25 out of the 27 properties.

In order to perform a representative analysis it was essential to understand the influence that the number of residents and their occupancy patterns have on the energy consumption. To obtain this, a house survey and face-to-face interviews were conducted in order to assess how the properties were used and provide an insight into the intensity of energy use. Appendix B shows a summary of the occupant survey results: from which it can be observed that occupancy is intermittent as a result of the varied work/life style. The majority of residents were unemployed or retired which indicates longer period dwelling occupancy hours. Properties that had at least one working adult had either a second unemployed adult, or one to three children living intermittently in the dwelling. From the occupant questionnaire, it was understood that over the weekend, 11 out of the 25 homes were mostly occupied, whereas 12 out of 25 residents indicated that they remained out most of the day during the weekends. These occupation patterns were also dependant on the weather patterns and time of the year.

METHODOLOGY

The study focused on obtaining consumption data during the first year of occupation from hand-over date. Collecting information from these dwellings was dependant on occupant availability and co-ordination in gaining access to the dwellings preferably in clustered time periods. Where possible, data was also collected using the IEDM reporting and data storage portal where real-time data is uploaded on an hourly basis. This service was only available to occupants that had their IEDM connected to the internet and agreed to have their information uploaded for the study.

Primary data was obtained from the installed IEDM located, typically, in the entrance hall of each property. To correlate and validate this data, utility meter readings were obtained from handover to its anniversary of occupation as this was the simplest approach to determining annual billed consumption (EST 2008).

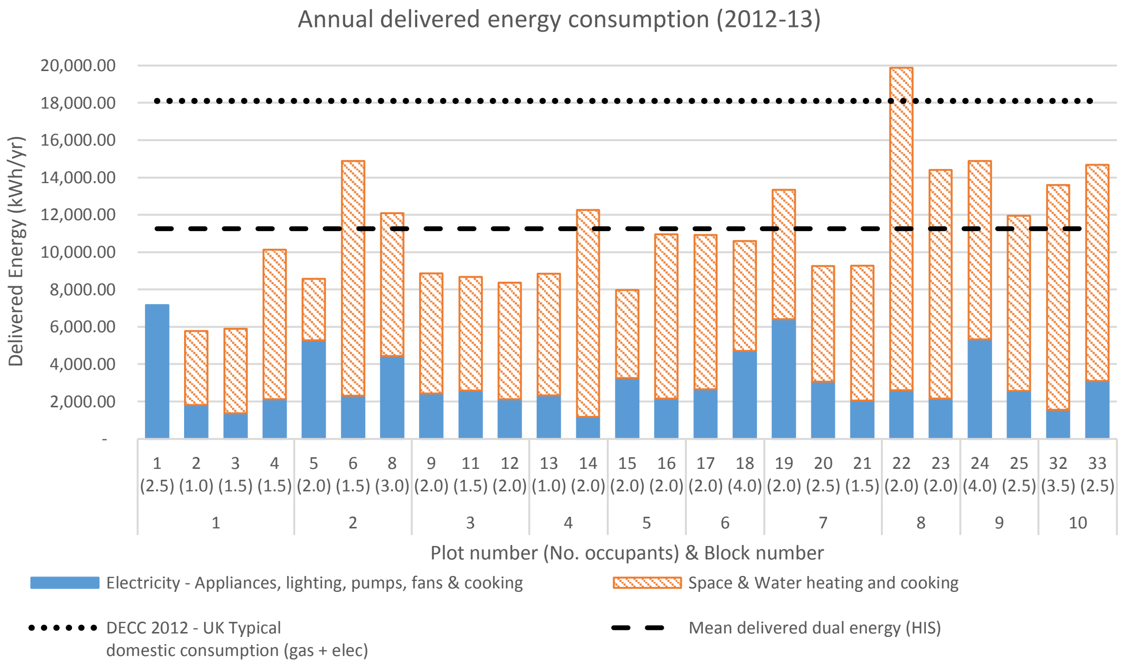
Data acquired from the properties was analysed to obtain total monthly consumption figures in kilowatt per hour (kWh) for both electricity and gas consumption as well as the heat generated by an ASHP (kWh) or electricity production from a solar PV array. The monitoring and calculation procedure was undertaken using the CIBSE TM22 methodology (Field & Davies 2006). Comparison with predicted energy figures was focused on space and water heating demand as characterised the efficiency of the envelope and building services. Electricity, unless used for heating purposes (ASHP) lighting, controls and use of pumps in the dwellings, was analysed separately. As this included un-regulated electricity which is occupant-led primarily by appliances. For this reason, space and water heating delivered by the different system technologies in the properties were analysed **closely** and compared with reference values.

Results were presented as annual energy consumption figures for heating with the cost of energy and the environmental impact in carbon emissions (kg of CO_2). In order to compare dwellings in the same block against a typical Kingdom HA home (Control dwelling), normalisation of energy use was made by floor area (m^2).

EVALUATION OF RESULTS

This section seeks to provide an overview of the total delivered energy consumption during the first year of occupation. It outlines how this impacts on cost and carbon consumption and provides a comparison to typical energy consumption levels in Scotland. As well as comparison against benchmarks, the results are paired with their relevant design-stage predicted energy consumption values For outlying purposes a comparison is also made between similar developments and house types within the HIS development (control house) and outwith it (Pittenweem Passive House by Kingdom HA).

Annual energy consumption

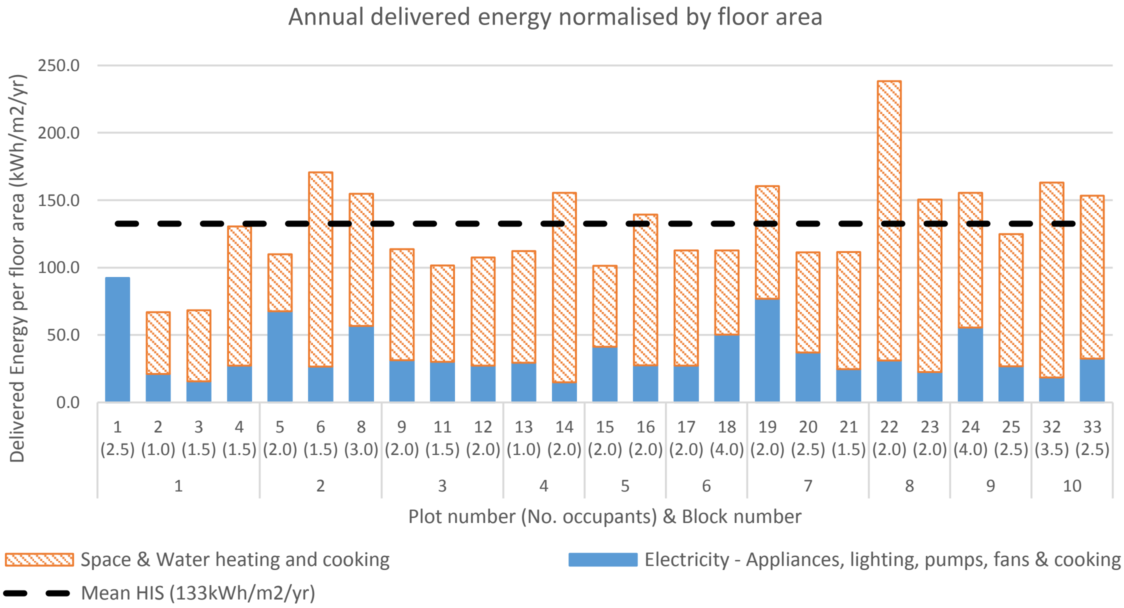


Graph 1: Annual delivered energy consumption over the first year of occupation: 2012-13

Annual delivered (metered) energy consumption for the homes is presented in Graph 1. In order to provide a comparative benchmark the graph also shows the most recent UK Sub-National Energy Consumption Statistics for gas and electricity at 18,094kWh/yr (DECC 2012b). Additionally they are compared with the average delivered energy of the whole development which stands at 11,200kWh/yr.

By comparison, 24 of the 25 dwellings performed better than the UK Sub-National Energy Consumption benchmarks (DECC 2012b). Ten of the dwellings consume more energy than the development energy consumption average with some dwellings consuming above 14,000kWh/yr and one in particular approaching 20,000kWh/yr; mainly as a result of a high number of occupants or higher quantities of electricity use to provide heating (e.g. ASHP, plots 5 & 19) or may have experienced a fault with their controls, for example plot 1 block 1 (no heating data obtained) where the occupant had continuous problems with his ASHP both in the controls and in its operation. Graph 1 also shows total electricity use, excluding net delivered energy (energy from renewables). It was observed, that the impact of electrical energy was smaller than that of energy for heat, nonetheless, electricity consumption should be minimised as the cost and environmental impact is higher than gas for space and water heating.

Normalised energy consumption comparison



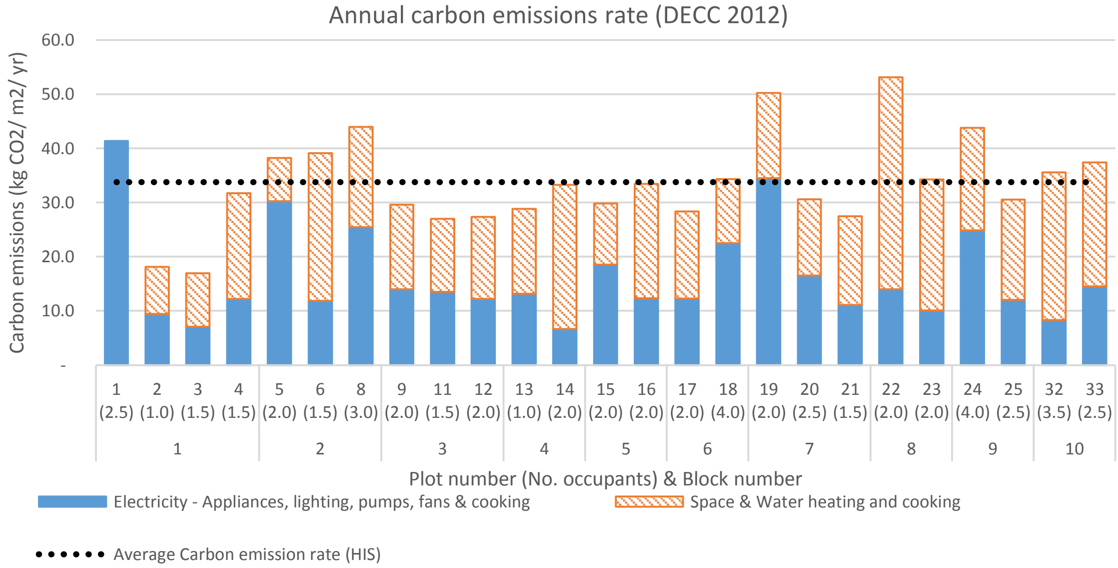
Graph 2: Annual delivered energy normalise by floor area

Graph 2 shows the normalised energy use by floor area, which is useful to facilitate a comparison between properties. As found in Graph 1, high consumers whilst closely linked with occupancy behaviour are more sharply affected by fabric and building services inefficiency. The highest energy consumer is plot 22 with 1 adult and two children living permanently in the property; consuming 240kWh/m2/yr. The rest of the properties show a consumption range between 70 and 170kWh/m2/yr. High electricity consumers include plots 1, 5 and 19 that utilise ASHP as their main heating source. The remaining properties show an average electrical consumption no greater than 25kWh/m2/yr, with the exception of plots 8, 18 and 24 which are occupied by 3 to 4 residents per household and consume >50kWh/m2/yr.

Normalised energy consumption by floor area for the control dwelling (plot 17) indicates that a quarter of its energy is used for electrical purposes (appliances, lighting & pumps/fans) and the remaining three quarters of energy is required for space heating. In comparison to similar properties, e.g. plot 18 (Passive House), this has a similar total energy consumption per floor area; however nearly half of its energy is used as electricity with the other half as heating. This provides an interesting comparison as the Passive House property is heavily insulated with high performing doors and enhanced solar gains while the control house is a standard 2010 Kingdom HA home. Similar energy consumption patterns appear in plots 5, 9, 12, 13, 20 & 21 with some expected minor variations in consumption, but the normalised energy is close to that of the control house. Plot 5 is an exception at 68 kWh/m2/yr for electricity, and 42 kWh/m2/yr for heat.

An analysis of plot 14 showed that a 1/8th of its energy consumption came from electricity while the remaining was for space and water heating. This property is occupied by a retired couple who experienced some complications in understanding the heating control system, moreover they seldom leave the property. A similar pattern was experienced in plot 16; occupied by an elderly retired couple who occasionally have grandchildren staying at home.

Annual Carbon Emissions



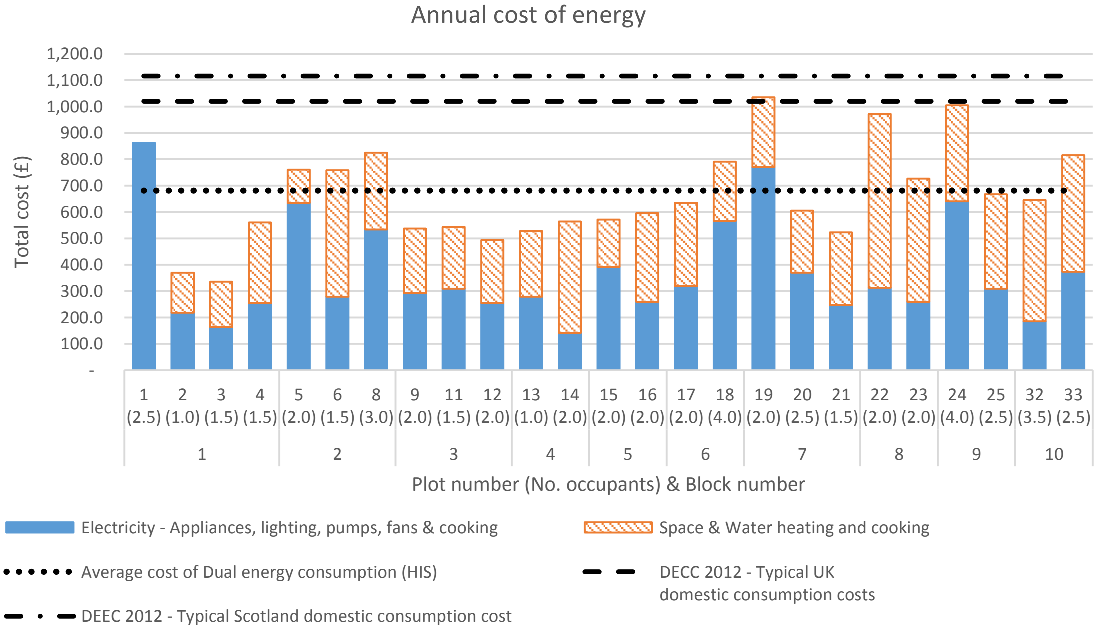
Graph 3: Total first year carbon footprint and carbon emissions rate using DECC 2012 factors

In the context of carbon emissions, total carbon emissions presented in Graph 3 for the flatted dwellings range from 17 to 44 $kgCO_2/m^2/yr$, semi-detached bungalows from 30 to 33 $kgCO_2/m^2/yr$, and terraced homes from 28 to 53 $kgCO_2/m^2/yr$. Differences are mainly identified with occupancy profile or because of high electrical use for appliances and heating devices (ASHP).
It is clear that 14 out of the 25 homes fall below the average emission value for the scheme of 34 $kgCO_2/m^2/yr$. This graph comprises both space and water heating and total electricity consumed in the household. The impact on carbon emissions is evident when households depend on the use of electricity for their heating, i.e. plots 1, 5 and 19 which are equipped with ASHP's. Plot 5 shows lower than average carbon emissions from electricity primarily due to its low occupancy. In comparison, plot 1 emits above 40 $kgCO_2/m^2/yr$ just on the electricity carbon impact alone, much higher than many other plots with combined carbon impacts. On other plots, the carbon impact of heating exceeds the average combined carbon emissions; as the case with plots 6, 14, 22, 23, 32 & 33, where heat outstrips electrical carbon impact. The remaining properties have a balanced effect of heat and electricity on its carbon footprint. Comparing results with the control house (plot 17), 10 out of 25 properties have performed similarly. Two plots (2 & 3) underperform the control house in carbon emissions, but are homes with low occupancy numbers and intermittent occupation.

Annual energy costs

In developments like the HIS, energy cost is of particular importance to the social landlord as well as to the residents. For the purposes of this analysis, the actual tariffs for delivered energy of heat in a bungalow and flat have been applied to the energy consumption figures in order to make a comparison. The cost structure applied to these calculations is derived from the gas equivalent cost for heating and the electricity cost delivered to the source properties. From the interview survey it was ascertained that some tenants had switched from standard metering to pre-paid meters during the monitoring period which can distort cost calculations. The most striking observation of the results was that electricity is the predominant energy cost compared with costs of heating. This is both due to consumption in some dwellings and also cost per kWh of each fuel. In flats, the average cost for heating was between £150 and £480 per year (£2.9 to £9.2 per week), in bungalows it was between £180 and £480 per year (£3.50 and £9.2 per week), and in terraced homes between £225 and £470 per year (£4.30 and £9.0 per week). Graph 4 (below) shows that households that consumed large amounts of electricity, with a higher cost per kW/h, spent higher that the household average of £680 per year. None of the plots reached the typical annual domestic dual energy consumption cost of £1,115 (DECC 2012b) which is a valuable benchmark but one that generalises on homes throughout the Scotland, of which a large proportion are poorly performing.

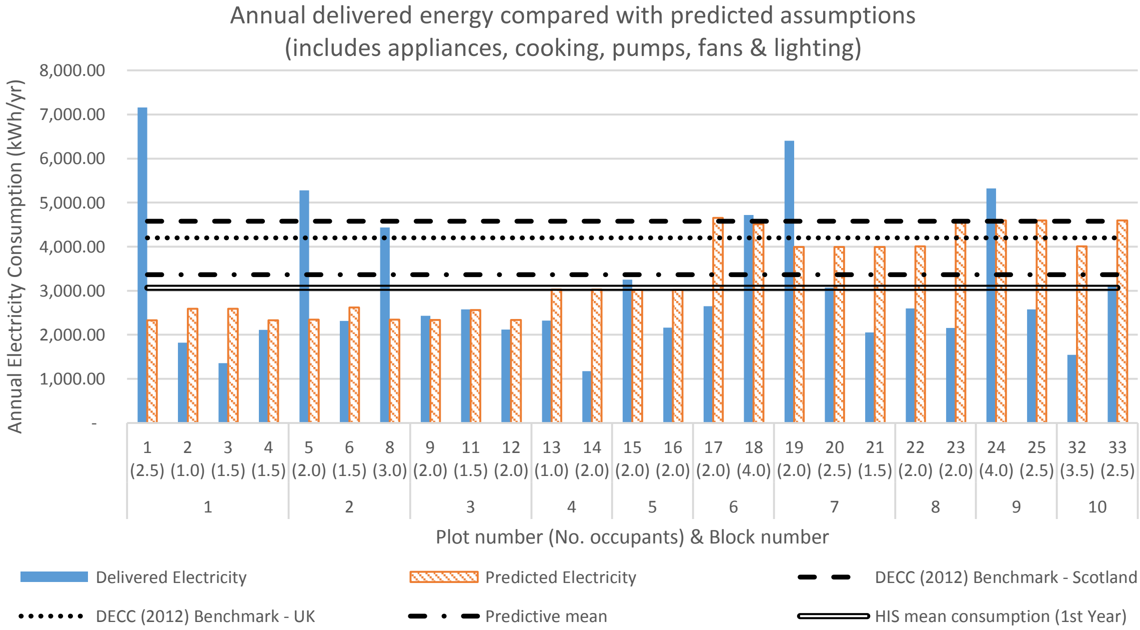
Properties with two or less occupants per dwelling generally paid less than the annual average with the exception of plots 20 & 32; which have 2.5 and 3.0 occupants respectively and characterise frugal energy living. Once again the properties with high energy cost of living are those with high electrical consumption either for heating purposes or because of energy hungry appliances.



Graph 4: Total cost to deliver both electrical and gas (heat) energy to the properties

Electricity consumption

In a scheme such as the HIS, electrical energy consumption can vary enormously between household given the diversity of technology installed, the occupancy and the house type.



Graph 5: Annual delivered electrical energy compared with predicted assumptions.

Graph 5 shows how the delivered (metered) energy consumed over twelve months compares against predicted calculations of assumed performance. Estimating electrical consumption in a dwelling depends on many parameters where occupant's behaviour plays a big part in the total energy use (Firth et al. 2008). Reduction in electricity demand through occupant behaviour changes can be between 10-30% (Palmborg, 1986) primarily through social habits. Prediction tools used in the built environment for compliance purposes do not consider any un-controlled electrical energy use but do include consumption for lighting; in relation with the number of assumed occupants, floor area, percentage of low emission fixed lighting outlets (BRE & DECC 2011) and daylighting in accordance to factors applied to the month of the year. It also accounts to electricity used for pumps and fans consumed by ventilation and heating technology (Yohanis 2012).

For the purposes of this project, and to produce a comparison base between the actual energy consumed, real-life energy consumption benchmarks have been used as well as average household energy statistical data (DECC 2013). According to Yohanis et al. (2008), there is a clear correlation between mean yearly electrical consumption and dwelling floor area. Various dwelling archetypes have been analysed and estimated total electricity consumption per floor area can be derived from them. Average monthly consumption figures per floor area indicate that terraced houses have a consumption between 2.5 and 3.9 kWh/m^2 (average 3.2 kWh/m^2) whereas semi-detached homes between 3.44 and 4.59 kWh/m^2 (average 4.0 kWh/m^2) (Yohanis et al. 2008). Sadly a figure for flatted accommodation was not quoted, but for the purposes of this project the lower end of terraced homes has been taken (2.5 kWh/m^2). These average figures have been used to produce a comparison base.

Referring to Graph 5, where energy is consumed by lighting, cooking, pumps, fans and appliances, it is clear that some dwellings are above the predicted value, others are very close, and some are lower than their annual estimates. From the graph the three properties with an ASHP are easily identified as high electrical consumers. Plot 1 (ground floor flat) consumes ≈3 times more electricity than its predicted consumption. This might be ascribed to its occupancy profile: where one of the adults was unemployed and utilises computers and the TV throughout the day and who has repeated problems in the operation of the ASHP. Similarly, plot 5 (ground floor flat) with an ASHP consumes 125% more electrical energy than the predicted. In plot 19 (terraced dwelling) the disparity is 60% with two retired adults and an intermittent occupancy pattern.

Bearing in mind governmental benchmarks (DECC 2012a), 20 out of the 25 properties fall below the 4,557kWh/year electrical consumption benchmark for Scotland. This benchmark is an average across Scotland and includes all age, house and occupancy types. It emphasises the fact that the properties in the HIS are unlike the majority of properties; with hybrid heating systems and poor fabric performance which require secondary electrical heating.

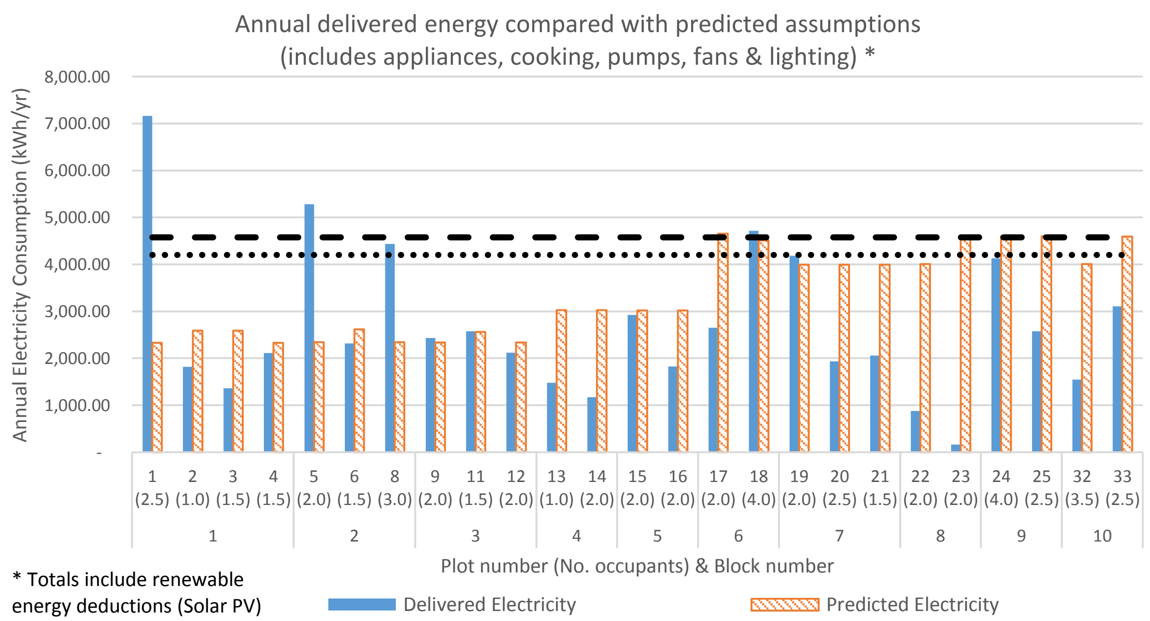
Interestingly, plot 18 which is a Passive House has a consumption above the benchmarked figures and slightly above the predicted floor area energy consumption. This may be ascribed to the high occupancy pattern where 4 adults with intermittent work patterns occupy the property. One of the adults is a housewife consuming electricity all day, the second adult works night and day shifts while the other two adults work and study at various times in the day. On visiting this property, many appliances were noted to be in operation. Additionally complaints of the high internal temperature conditions forced the occupants to use the ventilation system constantly.

Many of the properties were installed with low carbon technology which have the capacity to produce their own electricity. These included solar PV panels (solar tiles, hybrid and bolt-on) and micro CHP (6 kWh of heat and 1kWh of electricity). The reference values obtained from SAP, calculate the energy and carbon benefits they provide and evaluates the final performance of the property by applying these benefits of renewable energy sources. This can easily be applied to the analysed properties to obtain a net delivered energy. Table 1 analyses the impact of the Solar PV panels on the final electricity delivered. The average reduction of electricity is of 39% with panels providing as low as 10% (plot 15) of the delivered energy and as high as 92% in plot 23. These are directly proportional to consumption and size of the PV array. Plot 23 has a large 2.5kWp system with low occupant electrical consumption.

System Provider	Block	Plot & (No. Residents)	Heated space (m2)	Delivered Energy for Electricity (kWh/yr)	Solar PV electricity produced (kWh/yr)	Delivered electricity with Solar PV reduction (kWh/yr)	Reduction (%)
Porotherm	4	13 (1.0)	78.8	2,318	840	1,480	36%
Cube RE-treat	5	15 (2.0)	78.67	3,253	330	2,926	10%
Cube RE-treat		16 (2.0)	78.67	2,161	340	1,825	16%
FA 2016	7	19 (2.0)	83.2	6,405	2280	4,187	36%
FA 2013		20 (2.5)	83.2	3,071	1135	1,936	37%
Lomond - BW	8	22 (2.0)	83.42	2,600	1720	880	66%
Lomond - BW		23 (2.0)	95.76	2,157	1991	166	92%
CCG - iQ	9	24 (4.0)	95.8	5,323	1190	4,132	22%

Table 1: Impact of Solar PV electricity production on final delivered energy consumption

In line with Table 1 and Graph 5, Graph 6 below shows the net delivered energy of dwellings by deducting the energy generated from electricity by Solar PV technology. Examples of this are properties 19, 20, 22 and 23 that have large solar arrays and lower electrical use resulted in low net delivered energy. The exception is plot 01 which still shows higher than predicted consumption as a result of the high amounts of electricity needed to run the heating device. In plot 19 the solar PV generated energy has closely matched its predicted which demonstrates how much impact the array has on the final building energy figures.



Graph 6: Net delivered energy by electricity with the reduction of Solar PV generated electricity

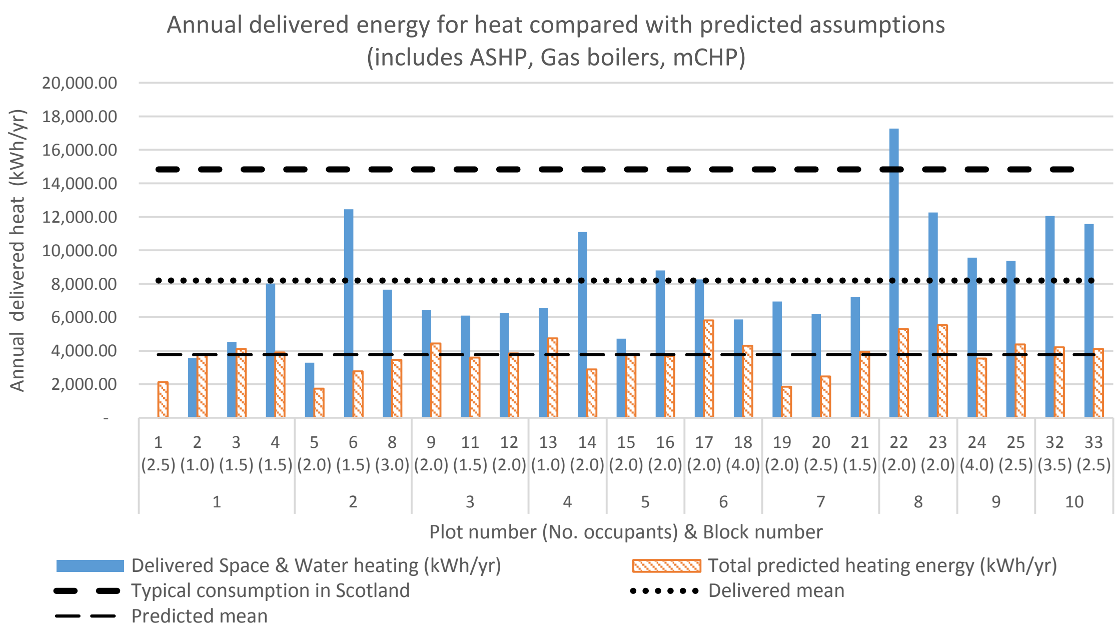
Heat consumption

Compliance modelling performed during the design process indicated that the energy efficiency and environmental carbon impact of a building is proportional to the dwellings envelope performance, ventilation performance, and the efficiency of the delivery of heat to the building. Property energy efficiency is calculated with aspirational design specifications and performance features (Kelly et al. 2012) . The quality of the model and how well the design is executed by contractors should deliver a building that performs closely to its predictions, this is seldom experienced, hence a performance gap.

The delivery of heat to the properties at the HIS came in various forms making it difficult to compare like with like. Instead, 12 month heat consumption by property were compared individually against the reference values obtained at design stage.

The HIS development showed a variety of technologies installed in each block of dwellings. The implementation of domestic building services ranged from heat pump technology using ASHP to micro Combined Heat and Power (mCHP). Some dwellings were fitted with conventional combination boilers and/ or solar hot water, for more information refer to Appendix A. Many properties were also fitted with Mechanical Ventilation with Heat Recovery (MVHR) systems which recover waste heat from wet room extract and supplies it back to living areas.

Graph 7 displays a comparison of delivered heat energy per household against that predicted at design stage. The average heat consumption over the first year was 8,200kWh/yr with figures as high as 17,200kWh/yr (110% greater) when using a conventional combination boiler. Lower consumption was experienced in properties with intermittent or low occupation (≈4,000kWh/yr); these were plots 2, 3, 5 and 15. Plot 5 used an ASHP consuming 90% more than predicted. Plot 1 also has an ASHP but unfortunately it suffered from technical issues in the installation of the heat meter and the adequate deployment of the IEDM produced difficulties in data retrieval.



Graph 7: Delivered & predicted heat energy comparison

The ASHP installed in plot 19 consumed just below 7,000kWh/yr against the value of 1,800kWh/yr predicted from the SAP calculation method. This represents close to four times the predicted energy consumption at design stage. Plot 19 was designed under the Scottish Building Standards Section 7 Gold level (SBS 2011) with space heating requirements of ≤30kWh/m^2/yr. Monitoring of the sample dwellings recorded total heat consumption (space & water heating) which made it difficult to provide a direct comparison. By subtracting the predicted water heating figures, an assumed space heating consumption was obtained. Predicted water heating at design stage was 1,550kWh/yr which results in an assumed space heating of 5,400kWh/yr. By normalising these figures by floor area (kWh/m^2/yr) a more relevant comparison can be obtained. With this in mind, plot 19 consumed 65kWh/m^2/yr which represents a two-fold rise against the SBS Section 7 Gold Standard. Using this same calculation, Plot 20 was designed under the Silver standard of 40kWh/m^2/yr, for predicted space heating. The delivered as-built figure was 52kWh/m^2/yr (4,300kWh/yr) which is 30% higher than the standard. Plot 21 was designed under the Bronze standard which requires Section 6 compliance where the Dwelling Emission Rate (DER) is lower than the Target Emission Rate (TER), a fair comparison would be against the control house in HIS which has a 35kWh/m^2/yr predicted value for space heating. Plot 21 consumed 87kWh/m2/yr in comparison with it's predicted of 22kWh/m^2/yr. Accurately separating space & water heating sub metering of heat was not conducted in the properties.

Higher heat delivery energy consumption against that predicted is observed in plots 5, 8, 9, 12, 14, 22, 23, 24, 25, 32 & 33 where dwelling occupancy has 2 or more residents. One property that has particularly surfaced above all is plot 6 consuming 4.5 times more energy for heat than the prediction. This property has intermittent occupancy patterns with occasional resident employment and a newly born child since handover, meaning heat was used more than usual. Added to this, the resident was not familiar with the heating controls and the benefits of the SHW panels that pre-heated water in the water cylinder was not being utilised to fuller benefit.

Plots 14, 23, 32 & 33 presented similar yearly consumption figures. In comparison with plot 14, plots 32 & 33 have 5 and 17m^2 respectively larger floor area. This is a semi-detached single storey property with 2 retired residents that infrequently leave the property. It shows a ≈4 times more heat energy than its predicted value. Plots 32 & 33, both semi-detached two storey properties, had a similar floor area but different occupancy. Plot 32 has two adults and one over, and another under, 16 year old occupants, with one adult frequently in the property. Although an energy frugal family, occupancy has taken over their consumption needs. Plot 33 was similar, in that one of the adults remains indoors throughout the day while the second adult works long hours and the under 16 year old is in education.

Plot 22 and 23 show >3 and >2 times respectively higher consumed heat energy than the predicted. There are many doubts on the performance of the breathing wall system. Residents complained that cooler air was entering the property which created thermal discomfort resulting in an increase in space heating needs. In the initial surveys of plot 23, it was brought to our attention that the pressure fans were not operating properly which were installed to aid the breathing wall system.

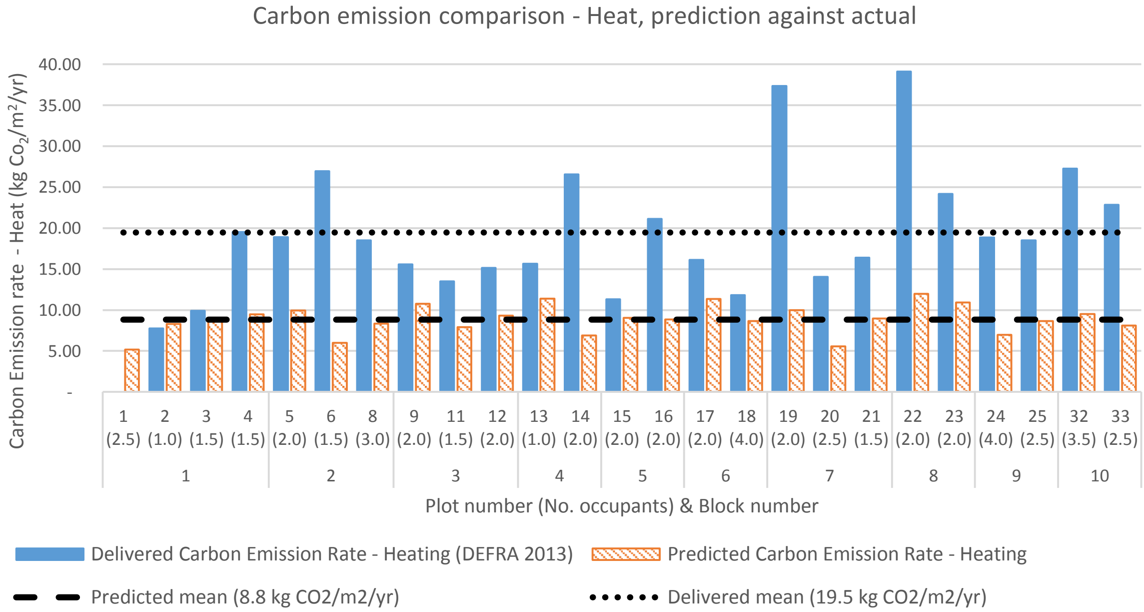
The control house (plot 17) consumed energy very close to the HIS average of 8,200kWh/yr but 2,000kWh/yr higher than the predicted mean of just below 3,800kWh/yr. The surplus of energy from that predicted was 42%, which can be considered low in comparison with other plots.

Plot 18, the Passive House, consumed just below 6,000kWh/yr for space and water heating. Utilising the methodology devised for plot 19, space heating consumption was just over 3,000kWh/yr or 32kWh/m^2/yr which is close to twice the Passive House target (15kWh/m^2/yr). Kingdom Housing Association had previously built another Passive House nearby and monitoring of this property showed that during the same period it consumed 3,273kWh/yr or 31kWh/m^2/yr also twice the target of the Passive House standard. What is interesting is that the two homes compare with each other in the space heating consumption considering that the property in HIS uses a combi-boiler and the other uses an ASHP.

As a form of a benchmark, average consumption of typical households in Scotland in 2012 of energy for space and water heating stands at 14,826kWh/yr (DECC 2012b), the majority of which comes from the 85% poorly performing existing building stock that will still be in use by 2050 (The Scottish Government 2013) the remaining 15% are poorly performing new homes built in line with relevant Building Regulations. Despite this, plot 22 has managed to surpass this benchmark by 2,400kWh/yr.

Carbon emissions comparison – Heat

The impact of carbon emissions from fuel consumed for space and water heating were calculated using the factors quoted by The Department of Energy and Climate Change (DECC) which are updated annually based on changes in generation emission factors (DEFRA & RICARDO-AEA 2013). The mean predicted value established for the HIS development was 8.8kgCO_2/m^2/yr in comparison with the delivered mean of 19.5kgCO_2/m^2/yr representing a doubling of carbon emissions between that predicted and that delivered.

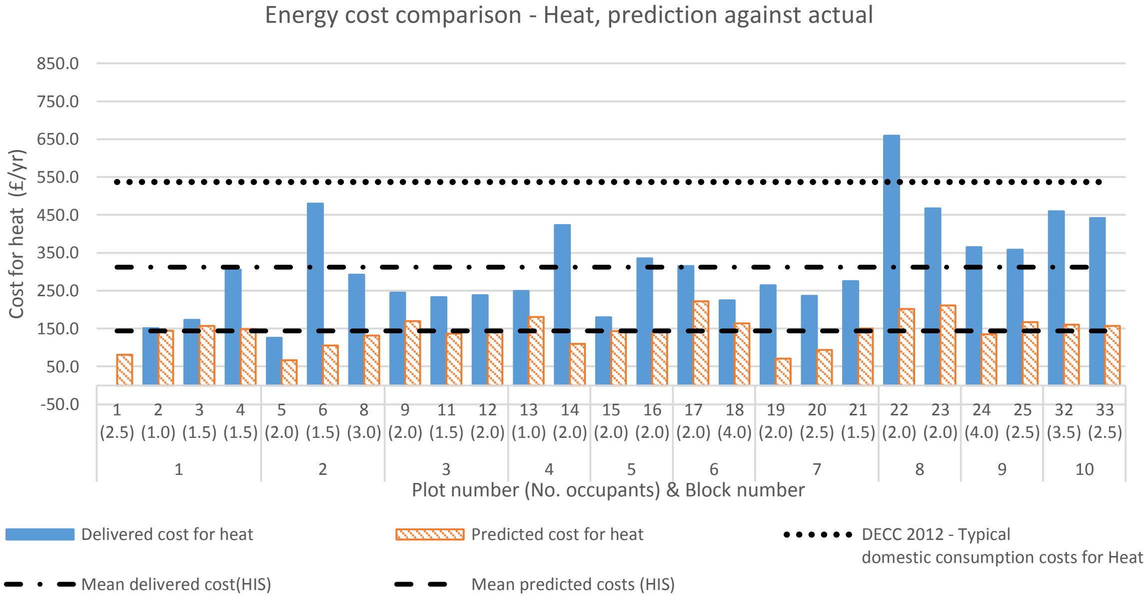


Graph 8: Carbon emissions from dwellings fuel for heat, comparison between consumed and predicted

The carbon emissions from the fuel consumed are a product of the total energy consumed during the first year of occupation. Eight properties exceeded the delivered mean which represent 32% of the sample population. The average surplus in carbon emissions varies from a 7% difference in a low occupancy flat, for example plot 3; to a high carbon emission property, plot 22 emitting 39 kgCO_2/m^2/yr (3.25 times more). Not far behind is plot 19 which utilises electricity as a primary fuel to power the ASHP for space and water heating. Electricity has a much higher carbon emission factor (0.448kgCO_2/kWh) than gas (0.189 kgCO_2/kWh) providing a higher impact differential between homes.

Cost comparison

It is hoped that sustainable and energy efficient homes like those built in the HIS are healthier, environmentally less of a burden and cheaper to run than the average private or public dwelling under current Building Regulations. However, according to The Scottish Government (2012), there are concerns about the affordability of keeping households warm and comfortable given the sharp increase in energy costs. The average direct debit domestic gas bill in Scotland increased in real terms by approximately 49% over the period 2007 – 2013 (DEEC, 2013). There is continuous pressure from international energy markets signalling further rises in fuel price; making it critical to build efficiently in order to avoid fuel payment difficulties among families. For this reason, enduring energy efficiency of dwellings will help provide a consistent low running cost while helping improve occupant comfort.



Graph 9: Energy cost comparison for the development

The average cost of heating of a UK dwelling is £537 per year (DECC 2012b) and Graph 9 shows that the mean cost for heat from the HIS development is £312 per year, 42% lower than the UK average. However this is £168 higher than the predicted mean annual cost using the prediction software required for regulatory compliance at design stage. Half of the properties in the study are close to or fall below that delivered mean. The high consumers and those that relied on electricity for their provision of heat appeared to be above this value reflecting the differences that might be experienced in off-gas grid developments where fuel choices are more limited.

CONCLUSIONS

The Housing Innovation Scheme was a bold attempt to trial and drive forward innovation in the construction of housing in Scotland. Kingdom Housing Association (KHA) have recognised the varied construction systems that innovate within the industry and have tried to implement them all in one development and learn from the outcomes that each have entailed. KHA were not only interested in the thermal performance of the properties; but were equally interested in build speed, cost and occupant satisfaction. Phase I part I of the Building Performance Evaluation (Jack, Currie, Bros-Williamson et al. 2013) reported on such issues as well as the early occupation building performance which gave the social landlord an indication of construction quality and thermal effectiveness.

This brave attempt to pilot different construction types and processes were additionally intended to test the efficacy of applying various performance standards now becoming a backbone of development, particularly in social housing. Although a relatively small sample size, the inclusion of a Passive House, Scottish Building Standards Section 7 Silver and Gold in the development; signified how the scheme was advancing towards Low and Zero Carbon housing policy, for example the Government's Homes that don't Cost the Earth (The Scottish Government 2012), Homes Fit for the 21^{st} Century (The Scottish Government 2011), and the stimulating roadmap set by Lynne Sullivan dubbed "The Sullivan Report" (Sullivan 2007) which has now reconvened setting out new challenges reviewing targets in a post-economic downturn and beyond (Sullivan 2013).

Comparisons between actual as-built electricity demand against predicted demand within the study was a challenge because the IEDM and meter readings gave total consumption and not segregated electricity use by appliances, lighting and other. The predicted electrical energy total used in compliance software ignores un-controlled energy use from appliances making a direct comparison difficult. Properties were not sub-metered in order to assess appliance daily usage and power output. Typical household electrical consumption, as analysed by Yohanis et al. (2008) provided an estimated benchmark of kWh per floor area used to compare the total electricity recorded per household in the HIS development. This showed that the heavy consumers, like those with an ASHP as their main space & water heating technology, consumed more than properties with a standard gas operating heating device (Graph 5). Some exceptions are made for high number of adult occupants per household. Graphs 6 and Table 1 show the impact of Solar PV technology on a dwellings annual delivered electricity; contributing on the lower end 10% of the dwellings energy while up to 92% in other lower consuming properties.

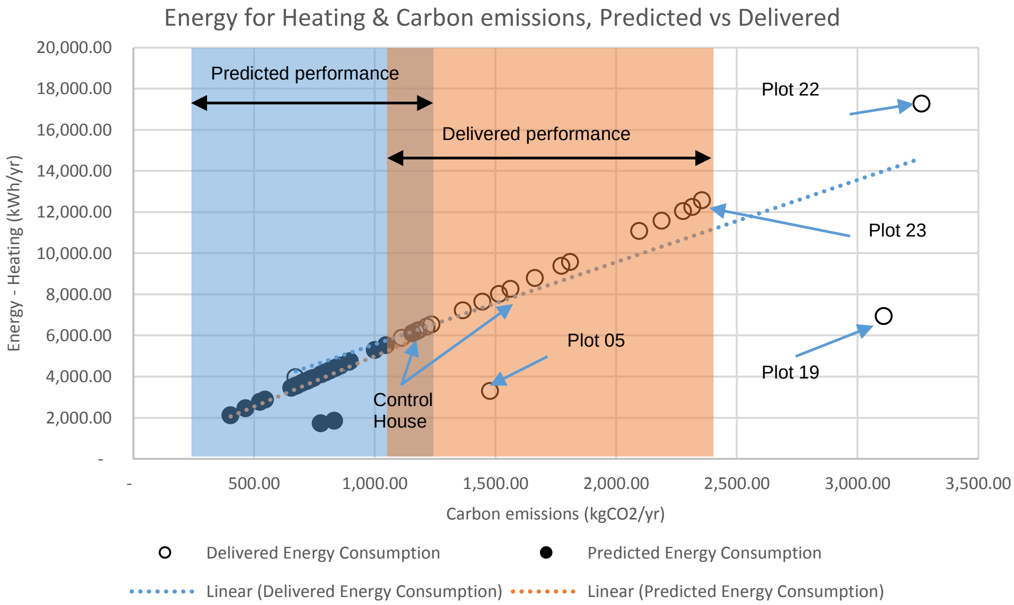
When analysing and comparing the delivered against predicted heat consumption various metering forms were encountered; for example, ASHP and Solar Thermal panels used a heat meter while standard gas meters registered consumption from combi-boilers or micro CHP's.
Differences between the predicted consumption showed a mixed bag of results. The overall results for delivered heat energy demand for the twenty five monitored dwellings were:

- Only one dwelling was <5% above the predicted
- Five dwellings consumed ≤40% above the predicted
- Five dwellings consumed between 60% – 90% more than the predicted
- Thirteen dwellings consumed between 100% and 350% more than it's predicted.

On average, a 122% increase in energy use over that predicted for heating purposes was obtained from the first year of occupation. Plot 2 showed that with the use of its solar thermal panel, heat consumption was below the predicted value, one reason for this indicated that the flat was used by a single working person with an intermittent occupation pattern, see Appendix C for more details.

In Graph 10 a comparison between the delivered and predicted energy for heating and its correspondent carbon emissions showed a distinct gap in performance. The predicted figures show that most properties achieve low energy consumption in line with low carbon emissions; most are clustered together showing a defined high energy performance.

The delivered scenario shows a more extensive spread of results with most properties consuming more energy with higher carbon emissions.



Graph 10: Comparison between Delivered and actual energy and carbon emissions

Although the energy results demonstrated a significant shortfall against the predicted consumption, it is important to recognise the scheme is a success in the approach and dedication of all the industry partners. The diversity and unification of various partners in one development has been a success which has created new stakeholder partnerships. The results show that an industry led change is required where aspirational performance has to be closely lined up with each other, reducing performance gaps by enhancing communication and site awareness in the execution of energy efficient methods. Each partner has used this project to learn and further fine tune their design.

It is important to point out that the data presented in this report is for the first 12 months of occupation. The first year of occupancy is a period in which residents are still un-familiar with heating controls and the use and benefits of renewable technology are unknown. This period acts as a learning curve for many people where thermostats are not used appropriately and energy is wasted where unfamiliar seasonal conditions combine with highly insulated envelopes. For this reason, the data presented can be somewhat distorted and not truly representative of a typical building performance; rather a behavioural reaction to a new home and an adjustment period. Data retrieved for the second year of occupation should show a more realistic account to the building performance.

Following this report of the first year of occupation energy consumption evaluation, a more defined and comprehensive study will follow. Representative dwellings from the Housing Innovation Showcase will be selected for long term detailed monitoring which will look at how dwellings can decline in performance over time. The overarching aim of the continued work is to accurately quantify the performance gap that has been observed in this document but also define the effects it will have on the properties life cycle. Field tests will be more defined in order to explore how the building performance affects the buildings environmental impact, occupant's health and comfort whilst also observing how electrical energy is used in a more detailed way.

APPENDICES

APPENDIX A - Dwelling IEDM proposed at design stage metering schedule

APPENDIX A - Dwelling IEDM proposed at design stage metering schedule						as at	18.06.12	V01
FIFE HOUSING INNOVATION SHOWCASE - DUNLIN DRIVE, DUNFERMLINE							05.08.13	V02
Block No.	**Plot No.**	**House number**	**Contractor**	**Integrated System**	**Additional Renewables**	**Proposed Monitoring**	**Proposed EWGECO Meter (3 Channel)**	**Actual Monitoring**
1	1	2 Ericht Drive	Assist Powerwall	None	ASHP	Import Electricity Meter, Import Gas Meter and ASHP Output	H300ERG	1. Import Electricity Meter, 2. Heat meter ASHP, 3. ?? (Gas)
	2	4 Ericht Drive		None	Solar Thermal	Import Electricity Meter, Import Gas Meter and Solar Thermal Output	H300ERG	1. Import Electricity Meter, 2. Heat Meter SHW, 3. ?? (Gas)
	3	6 Ericht Drive		None	N/A	Import Electricity Meter, Import Gas Meter and Water Usage	H300EWG	1. Import Electricity Meter, 2. Electric other, 3. Import Gas Meter
	4	8 Ericht Drive		None	N/A	Import Electricity Meter, Import Gas Meter and Water Usage	H300EWG	1. Import Electricity Meter, 2. Electric other, 3. Import Gas Meter
2	5	10 Ericht Drive	Campion Homes / Scotframe	None	ASHP & MVHR	Import Electricity Meter, Import Gas Meter and ASHP Output	H300ERG	Import Electricity Meter, Import Gas Meter and ASHP Output
	6	12 Ericht Drive		None	Solar Thermal & MVHR	Import Electricity Meter, Import Gas Meter and Solar Thermal Output	H300ERG	Import Electricity Meter, Import Gas Meter and Solar Thermal Output
	7	14 Ericht Drive		None	MVHR	Import Electricity Meter, Import Gas Meter and MVHR	H300ERG	Import Electricity Meter, Import Gas Meter and MVHR
	8	16 Ericht Drive		None	MVHR	Import Electricity Meter, Import Gas Meter and Water Usage	H300EWG	Import Electricity Meter, Import Gas Meter and MVHR
3	9	18 Ericht Drive	Stewart Milne	MVHR	N/A	Import Electricity Meter, Import Gas Meter and Water Usage	H300EWG	Import Electricity Meter, Import Gas Meter and MVHR
	10	20 Ericht Drive		MVHR	N/A	Import Electricity Meter, Import Gas Meter and Water Usage	H300EWG	Import Electricity Meter, Import Gas Meter and Water Usage
	11	22 Ericht Drive		MVHR	Micro CHP	Import Electricity Meter, Import Gas Meter and CHP Output	H300ERG	Import Electricity Meter, Import Gas Meter and CHP Output
	12	24 Ericht Drive		MVHR	Micro CHP	Import Electricity Meter, Import Gas Meter and CHP Output	H300ERG	Import Electricity Meter, Import Gas Meter and CHP Output
4	13	26 Ericht Drive	Campion / Porotherm	MVHR	Photovoltaics	Import Electricity Meter, Import Gas Meter and Solar PV Output	H300ERG	Import Electricity Meter, Import Gas Meter and Solar PV Output
	14	28 Ericht Drive		MVHR	Solar Thermal	Import Electricity Meter, Import Gas Meter and Solar Thermal Output	H300ERG	Import Electricity Meter, Import Gas Meter and Solar Thermal Output
5	15	30 Ericht Drive	CUBE Re: treat	Photovoltaics + MVHR	None	Import Electricity Meter, Import Gas Meter and Solar PV Output	H300ERG	Import Electricity Meter, Import Gas Meter and Solar PV Output
	16	32 Ericht Drive		Photovoltaics + MVHR	None	Import Electricity Meter, Import Gas Meter and Solar PV Output	H300ERG	Import Electricity Meter, Import Gas Meter and Solar PV Output
6	17	34 Ericht Drive	Campion Homes / Control Project	None	N/A	Import Electricity Meter, Import Gas Meter and Water Usage	H300EWG	Import Electricity Meter, Import Gas Meter
	18	36 Ericht Drive		MVHR	N/A	Import Electricity Meter, Import Gas Meter and MVHR	H300ERG	Import Electricity Meter, Import Gas Meter and MVHR
7	19	38 Ericht Drive	FUTURE: Affordable (David Blaikie)	ASHP + 3kW Photovoltaic + MVHR (2016 Regs)	None	Import Electricity Meter, Solar PVs and ASHP Output	H300EEE	Import Electricity Meter, Solar PVs and ASHP Output
	20	40 Ericht Drive		Gas Combi + 1kW Photovoltaic (2013 Regs), MVHR	None	Import Electricity Meter, Import Gas Meter and Solar PV Output	H300ERG	Import Electricity Meter, Import Gas Meter and Solar PV Output
	21	42 Ericht Drive		Gas Combi (Current Regs), MVHR	None	Import Electricity Meter, Import Gas Meter and MVHR	H300ERG	Import Electricity Meter, Import Gas Meter and MVHR
8	22	44 Ericht Drive	Lomond Homes	Photovoltaic	Voltage Optimisation	Import Electricity Meter, Import Gas Meter and Solar PV Output	H300ERG	Import Electricity Meter, Import Gas Meter and Solar PV Output
	23	46 Ericht Drive		Photovoltaic	Voltage Optimisation	Import Electricity Meter, Import Gas Meter and Solar PV Output	H300ERG	Import Electricity Meter, Import Gas Meter and Solar PV Output
9	24	48 Ericht Drive	CCG	None	Combined Photovoltaic/Solar Thermal, MVHR	Import Electricity Meter, Import Gas Meter and Solar PV Output	H300ERG	Import Electricity Meter, Import Gas Meter and Solar PV Output
	25	50 Ericht Drive		None	MVHR	Import Electricity Meter, Import Gas Meter and Water Usage	H300EWG	Import Electricity Meter, Import Gas Meter
10	32	4 Fyne Brae	Jack Bobin	None	None	Import Electricity Meter, Import Gas Meter and Water Usage	H300EWG	Import Electricity Meter, Import Gas Meter
	33	2 Fyne Brae		None	MVHR	Import Electricity Meter, Import Gas Meter and MVHR	H300ERG	Import Electricity Meter, Import Gas Meter and MVHR

Table 2: IEDM matrix of logging devices

APPENDIX B – DEMOGRAPHIC STUDY – DWELLING OCCUPATION STUDY

Block	Plot	House type	Hand over date	No. of Adults >16yr old	No. of Children <16yr old	Occupancy during week	Occupancy week-end	Notes
01	01	Flat	19/06/12	2	1	Intermittent occupation	Mostly in	1 adult unemployed
01	02	Flat	19/06/12	1	1	Adult - Not in home	Mostly in	Unemployed
01	03	Flat	19/06/12	1	-	1 week day shift, 1 week night shift	Occasionally working	
01	04	Flat	19/06/12	1	1	Working 4 days a week	Mostly out	
02	05	Flat	18/06/12	2	-	1 adult in all day, 2nd adult out most day.	Mostly out	1st adult disabled
02	06	Flat	18/06/12	1	1	Adult usually at home,	Mostly in	Intermittent work.
02	07	Flat	20/06/12	N/A	N/A	N/A	N/A	
02	08	Flat	18/06/12	2	2	1st adult working 9-6pm,	Mostly out	2nd adult unemployed
03	09	Flat	18/06/12	2	-	Both unemployed but 2nd adult out most day		Unemployed
03	10	Flat	18/06/12	N/A	N/A	N/A	N/A	
03	11	Flat	18/06/12	1	1	Intermittent occupation	Mostly in	
03	12	Flat	18/06/12	2	-	Intermittent occupation, 2nd adult out most of the day.	Mostly out	
04	13	Semi-detached	20/06/12	1	-	In the home most of the time	Always in	Disabled
04	14	Semi-detached	20/06/12	2	-	In most of the time –	Mostly in	Retired – Hospital visits
05	15	Semi-detached	20/06/12	1	-	Intermittent occupation	Mostly in	
05	16	Semi-detached	20/06/12	2	-	Intermittent occupation	Mostly in	Retired
06	17	Terraced	20/06/12	1	2	Intermittent occupation	Mostly out – ½ day	Unemployed
06	18	Terraced	20/06/12	4	-	1 adult always in, other adults working/ study	Mostly out	Varied occupation times, many appliances
07	19	Terraced	20/06/12	2	-	Intermittent occupation	Mostly out	Retired
07	20	Terraced	20/06/12	2	2	Intermittent occupation	Mostly in	1 adult in most day – other adult works
07	21	Terraced	20/06/12	1	1	Intermittent occupation	Mostly out	Unemployed
08	22	Terraced	19/06/12	2	-	Mostly out working	Mostly out	8am to 7pm
08	23	Terraced	19/06/12	1	2	Mostly in	Mostly out	Unemployed
09	24	Terraced	19/06/12	3	1	2 adults out working – 3rd adult in most of the time	Mostly out	3rd adult is over 16 yr old
09	25	Terraced	19/06/12	1	2	Mostly in the house	Mostly in	Unemployed
10	32	Terraced	25/06/12	2	1	1 adult working, 2nd in most of the time	Mostly out	2nd adult unemployed
10	33	Terraced	25/06/12	2	3	1st adult out working, 2nd adult in most of the time	Mostly in	2nd adult unemployed

Table 3: Demographic study of the sample dwellings

APPENDIX C – SURPLUS OF HEAT ENERGY USED OVER THE PREDICTED

System provider	Block	Plot (No. occupants)	Delivered energy - Heat (kWh/yr)	Predicted energy - Heat (kWh/yr)	Normalisation per m2 - Delivered	Normalisation per m2 - Predicted (SAP)	Percentage increase (%)
Powerwall -Enewall	1	1 (2.5)	-	2,124			-
Powerwall -Enewall		2 (1.0)	3,964	3,789	45.90	43.88	4.60
Powerwall -Enewall		3 (1.5)	4,532	3,890	52.49	45.05	16.51
Powerwall -Enewall		4 (1.5)	8,014	3,890	103.24	50.12	106.01
Campion	2	5 (2.0)	3,296	1,731	42.18	22.16	90.37
Campion		6 (1.5)	12,574	2,769	144.02	31.72	354.09
Campion		8 (3.0)	7,648	3,457	97.88	44.24	121.27
Stewart Milne	3	9 (2.0)	6,426	4,437	82.48	56.96	44.82
Stewart Milne		11 (1.5)	6,106	3,586	71.42	41.94	70.29
Stewart Milne		12 (2.0)	6,250	3,835	80.23	49.22	62.99
Porotherm	4	13 (1.0)	6,530	4,743	82.87	60.19	37.67
Porotherm		14 (2.0)	11,084	2,877	140.66	36.51	285.22
Cube RE-treat	5	15 (2.0)	4,717	3,759	59.96	47.78	25.47
Cube RE-treat		16 (2.0)	8,796	3,685	111.81	46.84	138.71
Control House	6	17 (2.0)	8,266	6,118	85.29	63.13	35.10
Passive House		18 (4.0)	5,875	4,296	62.53	45.73	36.76
FA 2016	7	19 (2.0)	6,937	1,855	83.37	22.30	273.88
FA 2013		20 (2.5)	6,192	2,455	74.42	29.51	152.23
FA 2010		21 (1.5)	7,217	3,944	86.74	47.41	82.97
Lomond - BW	8	22 (2.0)	17,272	5,291	207.05	63.42	226.45
Lomond - BW		23 (2.0)	12,250	5,531	127.93	57.76	121.48
CCG - iQ	9	24 (4.0)	9,568	3,533	99.87	36.88	170.81
CCG - iQ		25 (2.5)	9,380	4,384	97.91	45.77	113.94
BECO	10	32 (3.5)	12,044	4,206	144.38	50.42	186.37
BECO		33 (2.5)	11,577	4,105	120.90	42.87	182.02
						Average	**122%**

Table 4: Energy delivered against predicted – percentage of surplus in energy.

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